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Wayfinding behaviour in a multi-level building: A comparative study of HMD VR and Desktop VR

Yan Feng [*], Dorine C. Duives, Serge P. Hoogendoorn

Department of Transport & Planning, Delft University of Technology, Delft, the Netherlands

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ABSTRACT

Virtual Reality (VR) provides the possibility to study pedestrian wayfinding behaviour in multi-level buildings. Although VR has been applied increasingly to study pedestrian behaviour, it has remained unclear how different VR technology would affect behavioural outcomes in a multi-level building. The study compares the adoption of different VR technologies for pedestrian wayfinding studies, via investigating the difference in pedestrian wayfinding behaviour and user experience. Wayfinding experiments with two groups of participants were conducted using either HMD VR or Desktop VR. Pedestrian movement trajectory data were collected via the VR system and user experience data were recorded via a questionnaire. These data allow for direct comparison and detailed analysis of pedestrian behaviour and user experience between the adoption of two VR technologies. The results showed that technological differences have a significant impact on wayfinding task performance and head rotation change. However, the route choice, exit choice and user experience were overall similar between the two groups. These results provide empirical evidence supporting researchers to choose between immersive and non-immersive VR when study pedestrian wayfinding behaviour.

1. Introduction

Pedestrians perform wayfinding activities in buildings on a daily basis. Wayfinding here is defined as a decision-making process in which pedestrians determine the route to a destination and finding an exit to leave the building [1]. Performing wayfinding in large-scale and multi-level buildings, such as train stations, hospitals, and shopping malls, can be difficult because of the complexity of the three-dimensional environment [2]. That is, the complexity of finding one’s route and exit in multi-level buildings increases by the multiple floor layouts, complex spatial structures, many indoor objects, and moving along vertical distances [3–5]. In case of an emergency, pedestrian route and exit choice are of vital importance to their survival.

Traditionally, field experiments and surveys have been widely used to investigate pedestrian wayfinding behaviour under both normal and emergency situations (e.g., [6–11]). However, these methods have constraints in terms of experimental control, cost, and data accuracy for studying pedestrian wayfinding behaviour [12]. Most experimental studies focused on a single-level or simplified environment with an experimental area of limited size (e.g., [7,13–17]). Consequently, most experimental conditions featured in traditional pedestrian wayfinding studies differ greatly from actual reality where pedestrians are faced with more complex situations. Moreover, the accuracy of behavioural data is highly influenced by the sensor setup and techniques, and it often requires a large investment in labour to extract the collected data [12]. Additionally, it is time-consuming and challenging to obtain approval to perform a field observation or create an artificial experiment environment. Furthermore, there are ethical and financial constraints to create real and stressful situations to provide participants with a strong sense of presence to make them fully participate and keep focused on the task [21]. We suspect that the existing constraints of the traditional data collection methods (partially) induce a lack of studies featuring pedestrian wayfinding behaviour in large-scale and multi-level buildings [12].

To overcome the existing constraints of traditional data collection methods, the usage of Virtual Reality (VR) to investigate pedestrian wayfinding behaviour has become increasingly popular. With VR, it is possible to place participants in complex or hazardous situations that are costly, stressful or even impossible to simulate in the real world (e.g., [16,22–24]). VR allows researchers to perform controlled experiments that have high internal validity due to their experimental design and provide enhanced ecological validity due to the high-fidelity virtual environment [25]. Additionally, it provides the possibility of accurate

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[*] Corresponding author.
E-mail address: y.feng@tudelft.nl (Y. Feng).

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tracking and recording a large variety of data pertaining to pedestrian's movement and choice behaviour in complex environments, such as timestamp, pedestrian movement trajectory, head rotation, and eye movement.

Different VR technologies have been used to study pedestrian wayfinding behaviour, such as head-mounted-display (HMD) (e.g., [13,21,23,26–31]), Desktop VR (e.g., [17,32–35]) and cave automatic virtual environment (CAVE) (e.g., [36–38]). Although studies have demonstrated the effectiveness of VR to study pedestrian behaviour in a variety of cases, one unresolved issue is that the suitability of different VR technologies for pedestrian wayfinding behaviour study is still open to debate. Different VR technologies have different characteristics, it may cause people to perceive the virtual environment differently and behave in the virtual environment differently [15].

While VR technologies are more and more readily available to study wayfinding behaviour, researchers have limited insights into the impact of the adopted VR technologies on their research findings. To date, only a few studies have compared pedestrian wayfinding behaviour or evacuation behaviour using different VR technologies. For example, Santos et al. [15] found better performance with Desktop VR compare to HMD VR, Ruddle & Péruch [39] found no difference in wayfinding performance between HMD VR and Desktop VR, Ronchi et al. [37] showed consistent results of evacuation behaviour between a mobile-HMD and CAVE system in a tunnel emergency scenario. However, the above-mentioned studies did not directly compare the presentation of the same virtual environment using different VR technologies on pedestrian wayfinding behaviour across a variety of wayfinding tasks, and their experimental environments were relatively simple (i.e., single-level, limited size, and maze layout). In order to identify the influence of VR technology on pedestrian wayfinding behaviour in large-scale and multi-level environments, it is essential to directly compare VR technologies regarding their impact on pedestrian wayfinding behaviour and user experience in one environment.

The objective of this paper is to compare the adoption of different VR technologies (i.e., HMD VR and Desktop VR) for pedestrian wayfinding studies, via investigating the difference in pedestrian wayfinding behaviour and user experience. HMD VR and Desktop VR are two VR technologies that have been increasingly applied to study pedestrian behaviour. Compared to CAVE, which is very costly and requires a large space for the screen monitors or multiple television projection systems [40], HMD VR and Desktop VR provides cost-effective solutions. Moreover, the access to CAVE system is generally restricted to few institution laboratories, while HMD VR and Desktop VR are more accessible and affordable to a wider range of researchers who are interested in using VR. Meanwhile, compare with HMD VR, Desktop VR decreases technical complexity to implement and even provides lower-cost and off-the-shelf alternatives.

In the current study, we conduct VR experiments in which participants use either HMD VR or Desktop VR to perform a set of wayfinding tasks. In particular, pedestrian behaviour data (i.e., three-dimensional movement trajectories, head rotations, and gaze points) and participant's experience using VR (i.e., perceived realism, usability, feeling of presence, and simulation sickness) are collected synthetically. Previous studies from literature argue that the different features of HMD VR and Desktop VR may cause users to perceive the virtual environment differently and behave differently in the virtual environment (e.g., [41–44]). Thus, the collected data were analysed quantitatively to examine whether pedestrian wayfinding behaviour, such as route and exit choice, observation behaviour, and wayfinding task performance as well as user experience are different between HMD VR and Desktop VR. Accordingly, four hypotheses related to pedestrian wayfinding behaviour and user experience are formulated, namely:

H 1. There is a significant difference in route and exit choice behaviour (i.e., wayfinding strategy, paths, decision points, staircases, and evacuation exit choice) between the participants that adopted Desktop VR and HMD VR.

H 2. There is a significant difference in observation behaviour (i.e., head rotation and gaze point) between the participants that adopted Desktop VR and HMD VR.

H 3. There is a significant difference in wayfinding task performance (i.e., time, speed, and distance) between the participants that adopted Desktop VR and HMD VR.

H 4. There is a significant difference in user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that adopted Desktop VR and HMD VR.

There are three major contributions of this study, namely we (1) investigate pedestrian wayfinding and evacuation behaviour in a complex and multi-level building using VR, (2) provide a direct comparison of pedestrian wayfinding behaviour and user experience between two different VR technologies, and (3) recommend which VR technology to use to perform pedestrian wayfinding behaviour studies.

The paper is organised as follows. Section 2 provides an overview of used metrics to measure wayfinding behaviour and a review of VR - wayfinding studies. Section 3 describes the experimental method. Accordingly, Section 4 reports the results pertaining to pedestrian wayfinding behaviour in the virtual environment and user experience. Based on the results, Section 5 discusses the findings regarding differences in pedestrian wayfinding behaviour and user experience between the usage of HMD and Desktop VR. Finally, Section 6 presents the conclusions and future work of this paper.

2. Related work

The current study focuses on comparing pedestrian wayfinding behaviour in a multi-level building and user experience of the VR technology between the adoption of HMD VR and Desktop VR. Therefore, this section first provides an overview of commonly used metrics to measure pedestrian wayfinding behaviour in previous studies. Second, this section gives a summary of wayfinding studies that employed different VR technologies.

2.1. *Wayfinding behaviour in multi-level buildings*

Pedestrian wayfinding studies investigate how people orient themselves and navigate from an origin to a destination [45]. The term "wayfinding" was originally introduced by Lynch [46] where he defined human wayfinding as "a consistent use and organization of definite sensory cues from the external environment". Afterwards, multiple disciplines, such as engineering, psychology, and architecture have developed a wide variety of theories to understand this behavioural process. Jamshidi and Pati [47] classifies wayfinding theories into four categories, namely theories of (1) perception, (2) spatial knowledge development, (3) mental representation of spatial knowledge, and (4) spatial cognition. In general, the act of wayfinding can be viewed as a continuous problem-solving process requiring information about the environment [1,48–50], which contains the process of perception, cognition and decision making [47,49]. To be more specific, wayfinding refers to the process that people acquire information regarding their environment through their senses, understand and manipulate this information, establish a plan, transfer this plan into behavioural activities, and execute these activities in the environment [29,49–50].

Wayfinding behaviour has been widely explored in various spatial settings, including urban spaces (e.g., [51–54]) and buildings (e.g., [4,13,16,29,45,55–56]). Everyday people need to find their way in complex and multi-level buildings, such as offices, university buildings, train stations, hospitals, and shopping malls. Previous studies have observed the difficulty (e.g., disorientation, frustration, and stress) of people finding their way in complex and multi-level buildings [57–59]. Wayfinding in multi-level buildings has been considered complex due to the navigation of multiple floor layouts, (turning) staircases, differences in visual accessibility, and architectural differentiation. In general, literature identifies three levels of metrics to evaluate pedestrian wayfinding behaviour, namely decision making (e.g., wayfinding strategy, route choice, and exit choice), observation behaviour (e.g., head rotation and gaze point), and wayfinding task performance (e.g., time, speed, and distance) [13,56,58,60]. The explanations of these metrics and wayfinding studies in which these metrics are measured are given below.

Regarding the *decision-making level*, the usage of decision points and paths are found to be closely related to route choice and exit choice [29]. That is, if a person chooses a long route between an origin and a destination (exit), the number of decision points and length of path increase [29]. Literature shows that the arrangement of decision points, their linking paths, and the position of staircases contribute prominently to the experienced complexity of buildings [58]. Moreover, Hölscher et al. [61] illustrated that the adopted wayfinding strategy can also influence the efficiency of pedestrian wayfinding in multi-level buildings. Here, each element included at the decision-making level can be operationalized as follows:

1. *Decision points* - locations where pedestrians have more than one choice of direction to continue the way [45]. Studies showed that the number of decision points is positively related to the difficulty of wayfinding tasks [29,49,62].
2. *Staircases* - important vertical interconnections between different floors in a mulita-level building. Staircases could be seen as decision points on the vertical level. Literature found that floor changes that involve vertical movement on staircases can cause disorientation and hinder wayfinding performance [48,58–59]
3. *Paths* - the smallest segment connecting two decision points that people can move along [46,63]. When choosing between available paths, studies found that people prefer paths with longer lines of sight and are wider [64–67].
4. *Wayfinding strategy* - the strategy that people adopt to identify their optimal path. According to literature, wayfinding strategy can be categorised into three classifications, namely (1) the floor strategy: the individual first moves to the floor of the destination, (2) the direction strategy: the individual first moves to the horizontal position of the destination as directly as possible (irrespective of level-changes), and (3) the central point strategy: the individual finds the way by visiting the well-known parts of the building [61].

Wayfinding performance measures how well participants perform wayfinding tasks [4]. Often, wayfinding performance is measured using either travel time, travel distance, and/or travel speed. Weisman [68] provided four types of environmental elements that influence pedestrian wayfinding performance in buildings, which were investigated by many studies including (1) visual access to see other parts of the building from a given location (e.g., [69–71]), (2) the degree of architectural differentiation, which is the difference between objects in the building (e.g., [24,29,64]), (3) signs and room numbers to provide identification or directional information (e.g., [13,17,65,72–73]), and (4) plan configuration of the building (e.g., [55,58,74]). Therefore, these environmental factors should be taken into account while developing the virtual building for VR studies. Besides the environmental factors, literature has shown that personal factors, such as gender (e.g., [13,29,75]), age (e.g., [76–77]), and familiarity with the environment (e.g., [78–79]) can affect wayfinding performance. Moreover, the influence of interaction with other people on wayfinding performance has also been studied by [22,56,80–81].

Regarding the *observation behaviour*, pedestrians aid their navigation by looking around in the environment during wayfinding [82], and their gaze behaviour can reveal insights into the information acquisition process that supports the wayfinding tasks [66]. With the development of tracking technologies, such as eye-tracking, motion-tracking, it is possible to detect and collect people's head movements and eye movements during their navigation. Collected data can be used to measure how space is perceived and how specific elements attract individual's attention during wayfinding [83–84]. The usage of eye-tracking and head-tracking in wayfinding studies has been studied in real-life scenarios and virtual environments, such as buildings and urban spaces (e.g., [54,66,85–90]).

2.2. *Wayfinding studies in VR*

Virtual reality (VR) is defined as a system composed of interactive computer simulations that senses participant's position and responds to their movement, thereby giving participants the feeling of being immersed in a virtual environment [91]. Due to the rapid advancements of high-quality simulations and computer processing power, in combination with the reduction of computer power costs, VR has been applied increasingly to study pedestrian wayfinding behaviour (e.g., [21–22,36]). By using VR, researchers can create environments that are suitable for their research objectives with high experimental control, and let participants experience the virtual world through a continuous stream of high-realistic images and sound landscapes. Human performance in the virtual environment is generally influenced by the individual's level of experienced immersion in the virtual environment [92–93]. Regarding the level of immersion, VR studies can be generally categorised into two groups, namely non-immersive VR and immersive VR.

Non-immersive VR utilises common PC monitors or projections to allow participants to view the virtual environment. Participants typically use abstract interfaces (e.g., joystick, mouse, and keyboard) to control their movements. Several studies applied non-immersive VR to study pedestrian wayfinding and evacuation behaviour. For instance, Desktop VR has been used to study pedestrian wayfinding behaviour during evacuations (e.g., [17,32–35]). Projection-based VR has been applied to investigate pedestrian route selection during evacuations (e.g., [64,94]). Generally, using non-immersive VR, participants can still view the real world, which might limit their sense of immersion [95].

Immersive VR usually requires participants to wear a headset that blocks participants from their real-life environment. Participants interact with the virtual environment through specialist simulator control devices (e.g., controllers and gloves) and motion tracking hardware (e.g., eye, head, and motion tracking devices). One type of immersive VR is the Cave Automatic Virtual Environment (CAVE), which displays the virtual environment on huge screen monitors or multiple television projection systems simultaneously [40]. The CAVE has, for instance, been applied to investigate pedestrian wayfinding in high-rise buildings [3], tunnels [19,36,37,81], and train stations [38]. However, the installation of CAVE systems requires large spaces and the cost is relatively high. Therefore, studies using CAVE were conducted by few research groups with the resources for a CAVE [96].

Another type of frequently used immersive simulator is the head-mounted display (HMD), which typically features high-resolution displays. A large body of studies used HMD to investigate pedestrian wayfinding behaviour. One major research theme using HMDs focused on the influence of environmental characteristics on pedestrian wayfinding behaviour, amongst other things, the influence of signage [13,21,27–28], lighting conditions [23,29] and visual cues [24,26,30,71]. Another theme of studies focused on the impact of social influence on pedestrian wayfinding behaviour (e.g., [22,31,56,78]). Compared to CAVE, HMD VR can be built with high flexibility and low cost.

As mentioned in Section 2.1, spatial perception and cognition are important elements during wayfinding in real-life environments, which is the process of obtaining information through individual's senses [29]. The same applies to navigation in a virtual environment, where people need to perceive and obtain knowledge from the virtual environment. Various VR technologies are available in today's market. These VR technologies have different characteristics, such as levels of immersion, interaction ability, and in particular, the costs associated with their installation and use for research purposes vary greatly [37]. A number of studies showed that the usage of different VR technologies can have a varying impact on the user, particularly related to their sense of immersion and presence [41–43], usability [97], and motion sickness [98–99]. The differences in experiencing and perceiving the environments may cause people to behave differently during wayfinding and affect their wayfinding performance (e.g., [41–44]). Therefore, it has become important for researchers who are considering the usage of VR for wayfinding study to understand the assets and limitations of each VR technology.

Although studies have illustrated the effectiveness of VR to study pedestrian wayfinding behaviour, very few studies investigated the impact of different VR technologies on the actual pedestrian behaviour of participant's and their user experience. Several studies compared participant's performance of navigation tasks between Desktop VR and HMD VR [14–15,39,82]. Ruddle and Péruch [39] found that there were no differences in wayfinding performance and route knowledge between Desktop VR and HMD VR. At the same time, Ruddle et al. [82] found that people who used HMD VR travel quicker than people who used Desktop VR, while Hsieh et al. [14] found that people find destinations quicker using Desktop VR than HMD VR and Santos et al. [15] found better performance with Desktop VR compare to HMD VR. In these studies, the experimental environments were abstract mazes, and the tasks were relatively simple [100]. More recently, one study used a HMD and a PC screen to compare task performance in a multi-level indoor environment, which showed that the performance of navigation tasks was better in the Desktop VR than in the HMD VR [44]. However, another study compared pedestrian evacuation behaviour using smartphone-based HMD and CAVE and showed the consistency of pedestrian behaviour between the two VR systems [37].

In reality, pedestrians need to find their way in multi-level buildings and their wayfinding behaviour is affected by the layout of the architectural setting and the quality of the environmental information [100]. Simple and abstract environments have a significant lack of detailed environmental elements that aid pedestrian wayfinding, such as architectural differentiation, distinguishable decorations, visual accessibility, and information signage, which are of great importance for people perceiving the environment [68]. Moreover, the multiple floor layouts in multi-level buildings require movements on a vertical space, which further increases the complexity of wayfinding. Since the complexity and difficulty of wayfinding in multi-level buildings increase [50], findings featured in simplified environments cannot be directly generalised to multi-level buildings, which highlight the importance of investigating the differences in pedestrian behavioural outcomes in multi-level buildings and user experience between the adoption of different VR technologies.

In conclusion, VR technologies, especially HMD VR and Desktop VR, have been adopted increasingly to study pedestrian wayfinding behaviour. These VR technologies have very different characteristics regarding their usability and levels of immersion, presence, simulation sickness, which may cause people to perceive the virtual environment differently and behave differently in the virtual environment [41–44]. Currently, the impact of different VR technologies on the behavioural outcomes of the experimental studies, especially pedestrian wayfinding behaviour studies, is undetermined. Moreover, the few studies that compared the behavioural outcomes of different VR technologies featured relatively simple experimental setups. Consequently, the findings of these VR studies cannot be generalised to complex buildings. Thus, up to the moment, no studies directly compared pedestrian wayfinding behaviour in complex multi-level buildings as well as user experience between the adoption of different VR technologies. In our study, we fill this gap by conducting four wayfinding experiments in a multi-level building using both HMD VR and Desktop VR and comparing the resulting wayfinding behaviour and user experience of participants.

3. Materials and method

In the current study, we designed and conducted VR experiments with HMD VR and Desktop VR. The VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 944). This section presents a detailed description of the experimental method.

3.1. The virtual environment

The virtual environment featured a virtual building that comprises four floors. Fig. 1 shows the front view of the virtual building. Each floor features two parallel hallways, multiple intersections, four staircases and four elevators. There are five major exits on the ground floor (see Fig. 1). This virtual environment was originally developed as a VR research tool to study pedestrian wayfinding behaviour in a multi-level building (see [101]). The VR tool was developed using Maya and Unreal Engine 4 (UE4), which supports free navigation and collects pedestrian walking trajectories, head rotations, and gaze points automatically.

The virtual building is based on the building of the Faculty of Civil Engineering and Geoscience of the Delft University of Technology. In addition to the overarching geometry (i.e., the internal layout of the building, walls, escalators, and staircases), detailed environmental elements were also included in the virtual environment in order to improve the accuracy of the building's representation and increase its realism. Weisman [68] identified four classes of environmental elements that influence pedestrian wayfinding in buildings, including (1) visual access, which provides views that one can see other parts of the building from a given location, (2) architectural differentiation, which is the difference of objects in the building regarding size, colour, location, etc., (3) signs to provide identification or directional information, and (4) plan configuration of the building [55,58]. To implement these elements, detailed environmental objects were added in the virtual building accordingly, namely (1) glass windows to represent visual access, (2) various furniture such as chairs, cabinets, and tables that represent architectural differentiation, (3) evacuation signs, exit signs, and room numbers represent signs, and (4) floor plan represent plan configuration (see Fig. 2). The colour and texture of these environmental objects in the virtual environment were modelled as close as possible to realistically represent the real-world experience.

In the virtual environment, the participants have a first-person perspective. The participant's viewpoint is represented by a virtual camera. Participants could move in the virtual environment at a maximum constant speed of 140 cm/s. This speed limit was determined based on pilot tests, which to ensure that participants could have a similar walking pace as in real-life environments without causing simulation sickness (e.g., [102–103]).

3.2. Experimental setup

The versions of HMD VR and Desktop VR of the VR research tool were developed for this study. This sub-section introduces the general setup of the experiment and the setup of HMD VR and Desktop VR.

3.2.1. General technique setup

The VR experiment with the HMD group and the Desktop group were both conducted in the same room (4.6 m × 3.5 m) with a 2.5 m high ceiling, illuminated by fluorescent lighting, with neither reflective surfaces nor exposure to natural lighting. In both groups, the same computer was used, which was equipped with a AMD Ryzen 7 2700X with a 3.7 GHz CPU, MSI NVIDIA GeForce RTX 2080 graphics card, 16 GB system memory, and a Samsung 970 EVO MZ-V7E500BW 500 GB SSD. Participants also wore a pair of over-ear headphones to receive audio information and isolate themselves from the noise of the real-life environment. The software packages used for running the virtual environment were UE4 and SteamVR.

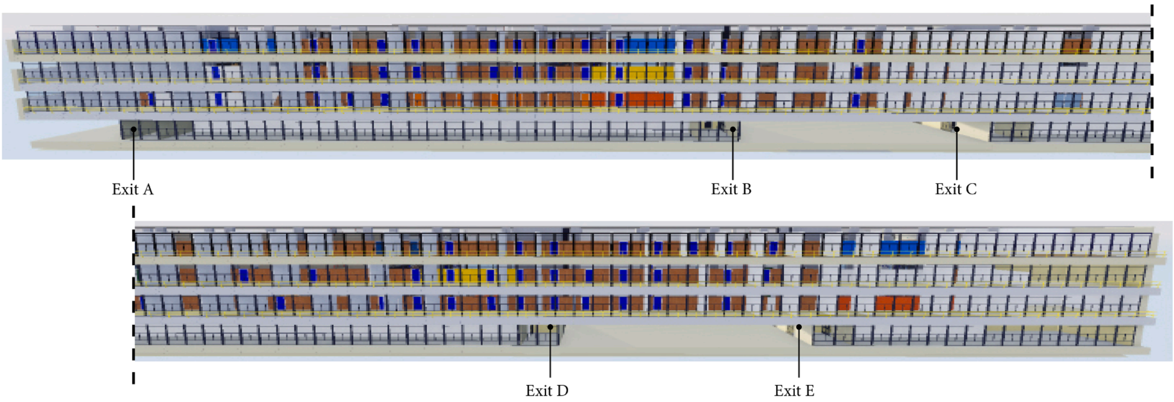


Fig. 1. The front view of the virtual building.

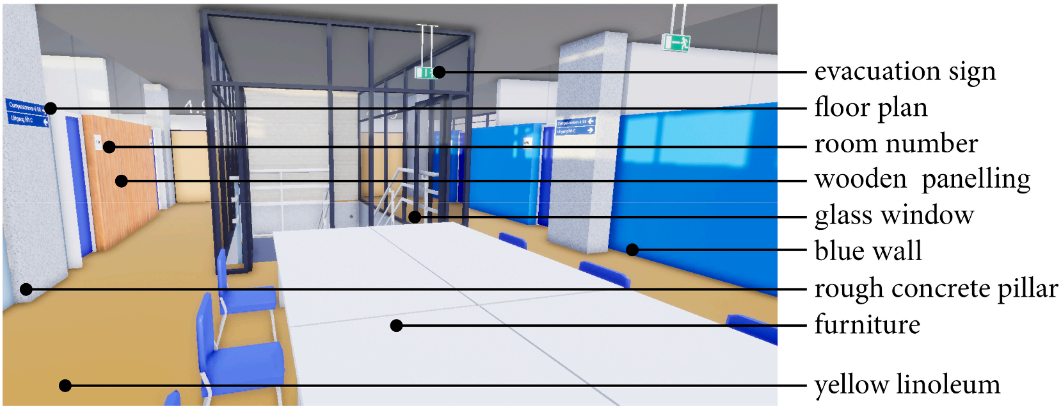


Fig. 2. A screenshot of the details in the virtual building.

3.2.2. *Setup of the HMD VR*

The HTC Vive system was employed for the experiment of the HMD group, which mainly included one HMD, one wireless hand controller and two base stations. Fig. 3 shows the devices included in the employed system. The HMD has 2160 × 1200 pixels combined resolution (i.e., 1080 × 1200 per eye), a 110-degree field of view, and a 90 Hz refresh rate for both screens.

Fig. 3. A participant using the HMD VR during the experiment.

A combination of an open-world navigation solution and a steering locomotion was adopted in the HMD group, which means participants had continuous movement with 'step-by-step' effects in the virtual environment when slowing down. The steering locomotion method was adopted because it generates less motion sickness compared to the teleportation method during the prototype tests. Moreover, this combination provides greater navigational benefits and is more natural to use than walking on a treadmill [39,104–105]. Participants used one hand controller to move through the virtual environment. By holding the home pad of the controller, the participant moved forward, and by releasing the home pad, the participant stopped moving. The direction of the movement was controlled by the participant's head orientation.

Tracking of the participants' positions and orientations in the virtual environment was achieved by means of the two base stations. These two base stations were placed opposite each other and connected via a sync cable. HTC Vive provides a room-scale technology that allows the user to walk freely, and the HMD features SteamVR Tracking technology which provides 360-degree head-tracking. The participants were tracked within a space of 3.4 m × 2.5 m in the experimental room.

3.2.3. *Set up of the Desktop VR*

The participants of the Desktop group viewed the virtual environment via a 24-inch desktop monitor (AOC G2460PF). The monitor is 565.4 mm long and 393.6 mm high. It has 1920 × 1080 resolution, a refresh rate of 144 Hz, and 1 ms response time. The monitor was placed on top of a rectangular table (90 cm × 150 cm) in the same experimental room as the HMD group (see Fig. 4). The horizontal distance between the monitor and the participant was approximately 60 cm.

A combination of an open-world navigation solution and a smooth artificial locomotion style was adopted for the Desktop VR. Participants' positions and orientations in the virtual environment were tracked via the virtual camera that represented participants' viewpoints. This combination allows participants to move artificially in the virtual building via the keyboard and mouse [97]. The participant moved forward by means of the keyboard key (i.e., 'w'), and changed the direction of view and movement by rotating the mouse. As a result of this navigation solution, participants' movement in the virtual building is continuous. Moreover, the setup allowed participants to have 360-degree freedom to move on the horizontal level and 360-degree views on both horizontal and vertical levels.

3.3. *Experiment design*

A single-factor between-subjects experimental design was used for this study to reduce the learning effects because of repetitive exposure. Literature identifies that repetitive exposure to the same environment affects pedestrian wayfinding performance [16,106]. Especially in the current study, the experimental environment and tasks are exactly the same for both groups. The VR experiments featured two different experiment settings but the only difference between both setups is the HMD VR versus the Desktop VR. Half of the participants were pseudo-randomly assigned to the HMD group and the other half to the Desktop group to ensure similar gender distributions between the two groups. During the experiment, the participants of both groups were asked to complete four wayfinding tasks during the experiment, including three wayfinding tasks under normal conditions and one wayfinding task under the evacuation condition.

Fig. 5 shows the abstract layout of the experimental environment. First, pedestrian wayfinding behaviour across the horizontal level was investigated. Participants were initially positioned in front of room 4.02 and were asked to find their way from room 4.02 to room 4.99 (see Fig. 5), which ensured they need to cross from one main corridor to the other and walk the length of the building. Second, pedestrian wayfinding behaviour (including staircase choice) at the vertical level was investigated. Participants were asked to find their way from room 4.99 to room 2.01. This task required participants to move between floors and walked the length of the building. Third, pedestrian wayfinding behaviour across both the horizontal and vertical levels was investigated. Participants were asked to find their way from room 2.01 to room 4.64, which forced them to switch floors and main corridors. The fourth task of the experiment was to investigate pedestrian wayfinding and evacuation choice during an evacuation scenario. When participants arrived at room 4.64, the evacuation alarm was triggered with a voice message: "Attention, please leave the building using the emergency exits as indicated. Do not use the elevators.". This evacuation alarm is the same alarm sound that is used during the real-life evacuation procedure at the modelled faculty building. Participants were asked to evacuate and find an exit. Once participants arrived at an exit, the experiment ended.

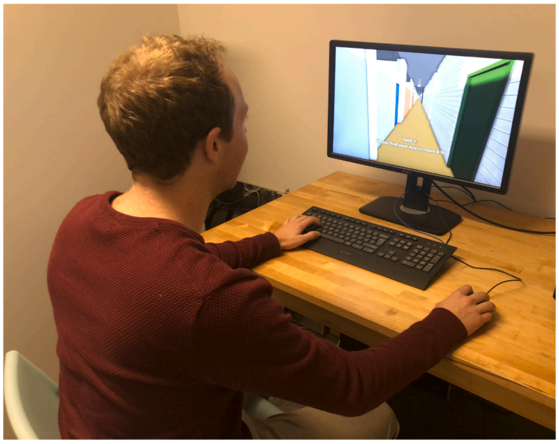


Fig. 4. A participant using the Desktop VR during the experiment.

3.4. *Experimental procedure*

A consistent experimental procedure was used for the HMD group and the Desktop group. The procedure included five major stages:

1. Introduction: When participants arrived at the experimental room, they first read the instruction letter about the experiment, including the usage of HMD VR or Desktop VR, the general procedure of the experiment and safety measures in case of any discomfort during the experiment. Participants were also informed that they had the right to stop the experiment at any time.
2. Practice: Participants then were instructed to wear the HMD or sit in front of the desktop monitor. During the practice session, participants were asked to find their way from A to B to C in a simple virtual scenario. The purpose of this session was to familiarise participants with using the devices and how to navigate through virtual space. This session ended when participants felt fully confident and comfortable with the devices to start the formal experiment, which generally lasted approximately three minutes. Afterwards, participants were teleported to the virtual building to start the formal experiment.
3. Formal experiment: At the beginning of the formal experiment, participants were initially located in front of room 4.02 in the virtual building. The task information appeared on the screen to instruct participants to begin the first task. Once participants arrived at the task's destination, the next task was depicted. At the beginning of the fourth task, the evacuation alarm sound was automatically triggered. Once the participants reached one of the exits, the formal experiment was terminated and a message popped up showing 'Task complete'.
4. Post-experiment questionnaire: Once the participants completed the formal experiment, they were asked to fill in the post-experiment questionnaire in the same experimental room.
5. Health check: After filling the questionnaire, the experimenter checked with participants whether they felt any discomfort. Participants were only allowed to leave if they had a normal state of health.

3.5. *Data collection and analysis*

Two types of data were collected during the experiment, namely the behavioural data pertaining to the participant's movement in the VR environment and questionnaire data pertaining to user experience with the VR system. In order to identify significant differences regarding pedestrian behaviour data and questionnaire data between the two groups, a two-step statistical procedure was applied. First, the Shapiro–Wilk test was conducted to test distribution normality, which is an appropriate normality test for sample sizes that are below 50 [71]. Second, if the data was found to be normally distributed, the independent *t*-test was carried out to determine whether the differences were significant. Otherwise, the nonparametric Mann-Whitney U test was used. For all statistical analyses, the significance level was set at 0.05. Moreover, the effect size was also calculated.

3.5.1. *Pedestrian behaviour data*

Each participant's behaviour in the virtual environment was recorded. Participant's positions, head rotations (i.e., yaw, pitch, and roll), gaze points, together with timestamp were recorded at a frequency of 10 Hz within UE4. According to the identified wayfinding behaviour metrics in literature (Section 2.1), these data were translated into three

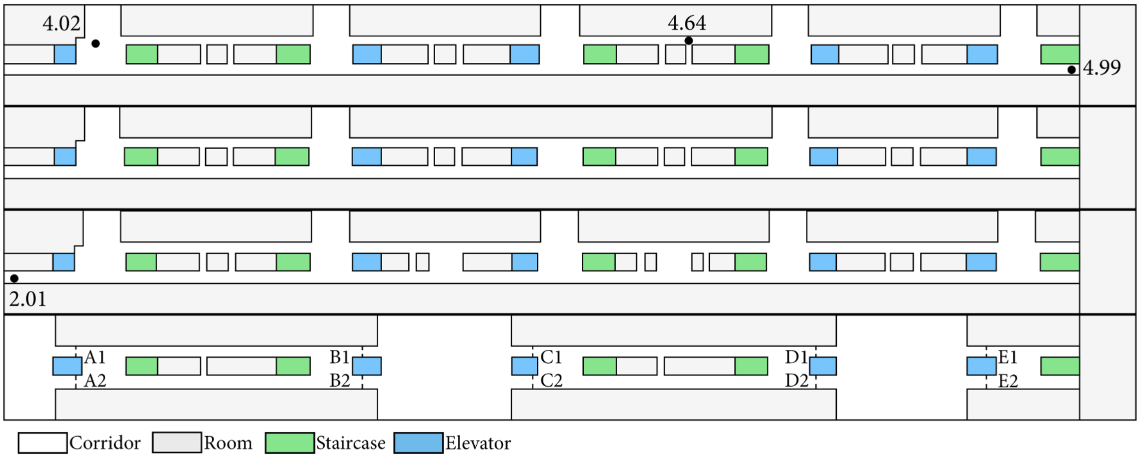


Fig. 5. The layout of the virtual environment, A1-E2 are exits.

types of metrics regarding participant's wayfinding behaviour, namely (1) participant's decision making (e.g., wayfinding strategy, route choice, and exit choice), (2) observation behaviour (e.g., head rotation and gaze point), and (3) wayfinding task performance (i.e., travel time, travel distance, and travel speed). Based on the definition of these metrics in literature, the explanation of each adopted metric for data analysis is listed below:

1. ***Participant's decision making***

(1) *The wayfinding strategy*: The usage of the wayfinding strategy of each participant during each task is analysed. Here, we take the start position, room 4.02 as the well-known parts of the building to distinguish between central point strategy and floor strategy, namely to identify whether participants pass room 4.02 during the current task and the precious task. For instance, if one participant passes room 4.02 during task 2 and accordingly passes 4.02 again during task 3, we record the central point strategy; if one goes directly to the fourth floor and does not pass room 4.02 again during task 3, we record the floor strategy for this participant. Fig. 6 illustrates the wayfinding strategies that were adopted by one participant during the experiment. This participant used the central point strategy during task 1 (orange trajectory), the direction strategy during task 2 (green trajectory), and the floor strategy during task 3 (blue trajectory) and task 4 (red trajectory).

(2) *The usage of paths*: A path is defined as the smallest section connected by two decision points that located along the two big parallel corridors. The distribution of used paths is analysed.

(3) *The usage of decision points*: Since in the current experiment participants face the same number of decision points, we analyse the distribution of decision points that each participant used, namely the decision points where a participant decides to cross from one side to another side of the building.

(4) *The usage of staircases*: The distribution of staircases used by participants is analysed. Fig. 7 shows the distribution of one individual's usage of path, decision point, and staircase during task 2.

2. ***Observation behaviour***

In order to better understand participant's observation behaviour during wayfinding tasks, both head rotation data and gaze point data is analysed. For the head rotation analysis, in order to limit noise caused by participants who shake their heads while walking [24], we only focus on head rotation data along the Yaw axis. The Yaw movement is the head rotation on the horizontal plane between −180° and 180° (i.e., rotate the head left/right). Participants' average head rotation change $\overline{Y}$ during each task is calculated by Formula 1 and 2:

$$Y(t) = min(360 - |Y_{t+dt} - Y_t|, |Y_{t+dt} - Y_t|.) \quad (1)$$

$$\overline{Y} = \frac{\sum_1^T Y}{T} \quad (2)$$

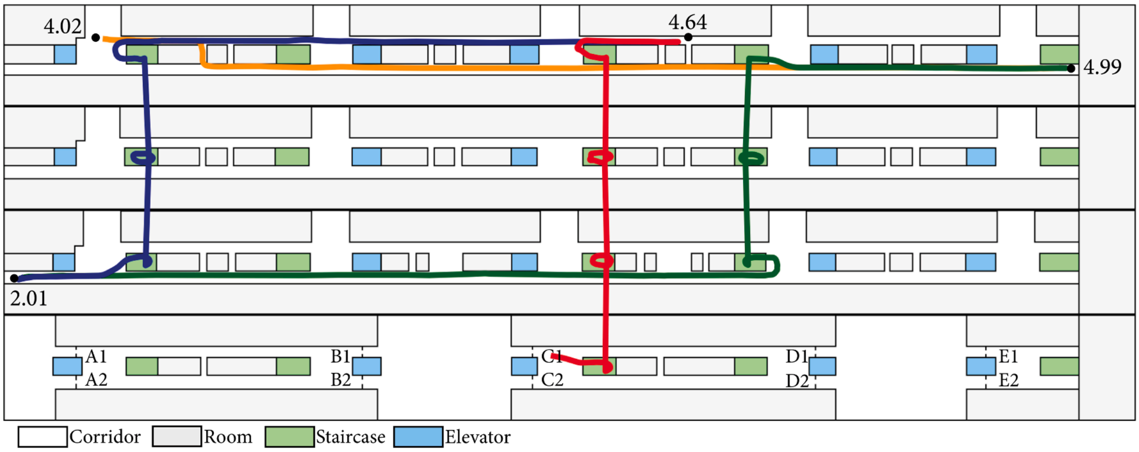


Fig. 6. An illustration of different wayfinding strategies adopted by one participant during the experiment.

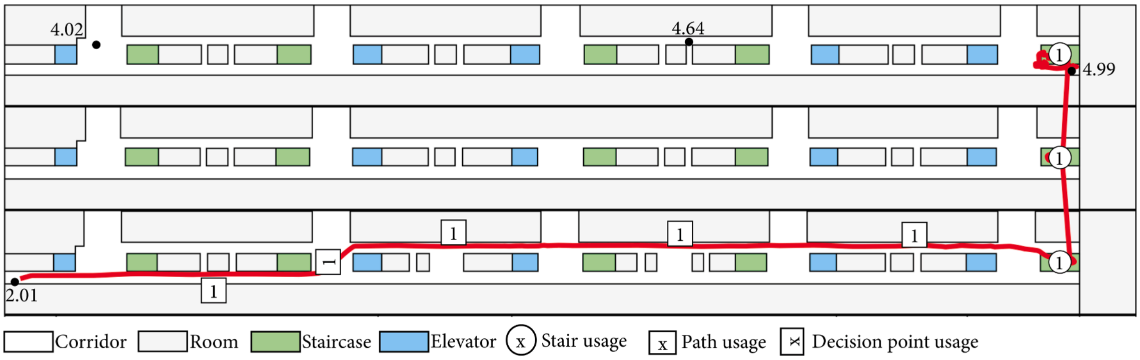


Fig. 7. Distribution of one individual's usage of path, decision point and staircase during task 2.

where *Y(t)* is the instantaneous rotation change, Y_t is the current Yaw coordinate of the participant at *t* timestep and *dt* is the timestep interval, *T* is the travel time of the task.

The point of interest in the virtual environment is determined using a gaze point analysis. Gaze points identify the locations where participants rotate their head and the direction of the head hits the geometry in the environment. Please note, in the current paper, we calculated gaze points based on participants' head directions. We assume that participants always look straight ahead and when participants look at certain objects in the virtual building, the direction of the head hits the geometry in the environment and counts as a gaze point. The density of the dots indicates the number of gaze points and time spent on the AOI (area of interest). The denser the gaze points, the longer participants looked towards that area and the slower the walking speed of participants passing that area. More sparse distribution of the dots indicates that fewer gaze points were created, which means that participants paid less attention to that area and passed by quickly.

3. *Wayfinding task performance*

Wayfinding task performance is measured in terms of travel time, travel distance, and average speed of each task in both groups.

Travel time is defined as the time participants spent from the starting location to the destination location during each task. It is one of the important criteria to measure the performance of pedestrian wayfinding tasks [29].

Travel distance is defined as the total distance that participants travelled from the starting location to the destination location during each task. The travel distance is the sum of travel distance on the corridor D_c and travel distance on the staircase D_s, which are calculated using Formula 3 and 4:

$$D_c = \sum_{1}^{T_c} \sqrt{(x_{t+dt} - x_t)^2 + (y_{t+dt} - y_t)^2} \tag{3}$$

$$D_s = \sum_{1}^{T_s} \sqrt{(x_{t+dt} - x_t)^2 + (y_{t+dt} - y_t)^2 + (z_{t+dt} - z_t)^2} \tag{4}$$

where x_t, y_t, z_t, are the x-coordinate, y-coordinate, and z-coordinate of the participant at *t* timestep, *dt* is the data recording timestep (0.1 s). T_c is the travel time on the horizontal plane and T_s is the travel time on the vertical plane.

The average speed per task is computed for each participant by dividing the total travel distance by the total travel time spent during each task.

3.5.2. *User experience data*

The personal features and experiences of each participant regarding the virtual experiment were collected via the questionnaire. The questionnaire contained five sections: (1) participant's information, which included their socio-demographic information and their experience with VR, computer gaming and the experimental building in real-life, (2) the face validity questionnaire, which assessed whether a simulator measures what it is intended to measure [107], (3) the Simulator Sickness Questionnaire [108], which determined if participant's experience sickness throughout the experiment, (4) the System Usability Scale [109], which assessed the usability of the applied VR systems, and (5) the Presence Questionnaire [110], which measured participant's sense of presence in the virtual environment. This comprehensive questionnaire was used in order to ensure that the authors are able to study and compare user experience in the virtual environment in great detail.

3.6. *Participant recruitment & characterisation*

A priori power analysis was conducted using G*Power 3.1 in order to estimate the required sample size [111]. The result indicated that a total sample of 68 participants would be needed to detect large effects (d = 0.80) with 90% power using an independent samples *t*-test between means (two-group). A total sample of 43 participants would be needed to detect large effects (w = 0.50) with 90% power using the Chi-square test. Effect size describes the magnitude of differences found between two groups and larger differences lead to more powerful tests [112]. In this study, the effect size is chosen based on Cohen's definition of large effect size [113] and similar studies [114–115] that adopted effect sizes of 0.7 and 0.69, respectively.

Participants were recruited by means of advertisements at the Delft University of Technology (i.e., e-mails, websites, flyers, posters, social media, and in-classroom promotions). In this stage, potential participants were told that the purpose of the experiment was to investigate the usage of VR to study pedestrian behaviour. In order to not bias participants' behaviour, no information was provided regarding the actual VR experiment.

The VR experiments were carried out from 27th November 2019 to 18th December 2019. In this study, a total sample of 72 participants joined the experiment, 38 participants took part in the HMD group and 34 took part in the Desktop group. All participants volunteered to take part in the experiment and did not receive compensation for their participation. All participants had normal or corrected-to-normal visions and normal hearing capabilities. Two participants from the HMD group asked to take a break during the experiment and did not finish the whole experiment, so they were excluded from further analysis.

The participants were between 22 and 64 years old (M = 27.85, SD = 6.83) in the Desktop group, and between 17 and 41 years old (M = 28.66, SD = 6.00) in the HMD group. The Mann-Whitney U test showed that there was no significant difference in age between the two groups (U = 486.5.5, p = 0.07, d = 0.13). Table 1 presents a summary of the characteristics of the participants in two groups. All participants in both groups had a certain familiarity with the faculty building featuring in the

Table 1
The descriptive information of participants.

Descriptive information	Category	HMD	Desktop
Gender	Male	17 (47.22%)	24 (70.59%)
	Female	19 (52.78%)	10 (29.41%)
Familiarity with the faculty building	Not at all familiar	0 (0.00%)	0 (0.00%)
	A-little familiar	1 (2.78%)	5 (14.71%)
	Moderately familiar	5 (13.88%)	4 (11.76%)
	Quite-a-bit familiar	9 (25.00%)	7 (20.59%)
	Very familiar	21 (58.34%)	18 (52.94%)
Highest education level	High school or equivalent	5 (13.88%)	0 (0.00%)
	Bachelor’s degree or equivalent	6 (16.67%)	10 (29.41%)
	Master’s degree or equivalent	19 (52.78%)	21 (61.77%)
	Doctoral degree or equivalent	6 (16.67%)	3 (8.82%)
Previous experience with VR	Never	11 (30.55%)	7 (20.59%)
	Seldom	18 (50.00%)	15 (44.12%)
	Sometimes	6 (16.67%)	9 (26.47%)
	Often	1 (2.78%)	0 (0.00%)
	Very often	0 (0.00%)	3 (8.82%)
Familiarity with any computer gaming	Not at all familiar	6 (16.67%)	3 (8.82%)
	A-little familiar	6 (16.67%)	6 (17.64%)
	Moderately familiar	8 (22.22%)	5 (14.71%)
	Quite-a-bit familiar	7 (19.44%)	7 (20.59%)
	Very familiar	9 (25.00%)	13 (38.24%)

VR experiment. Most of the participants received a bachelor’s degree or higher level of education. More than half of the participants had never or seldom tried VR before; 80.55% in the HMD group and 64.71% in the Desktop group. The familiarity with computer gaming experience was relatively high (i.e., between moderately familiar and very familiar) in the HMD group (66.66%) and the Desktop group (73.54%). Original questions related to ‘Familiarity with the faculty building’, ‘Highest education level’, ‘Previous experience with VR’, and ‘Familiarity with any computer gaming’ can be found in Appendix A. Chi-square tests showed that there were no significant differences found between two groups regarding gender ($X^2(1, N = 70) = 0.71, p = 0.399, phi = 0.24$), familiarity with the faculty building ($X^2(3, N = 70) = 3.20, p = 0.361, v = 0.21$), the highest level of education ($X^2(3, N = 70) = 7.05, p = 0.070, v = 0.32$), experience with VR ($X^2(4, N = 70) = 5.71, p = 0.222, v = 0.29$) and familiarity with computer gaming ($X^2(4, N = 70) = 2.36, p = 0.669, v = 0.18$). The Chi-square and Mann-Whitney U tests are statistical hypothesis tests that identify whether a statistically significant difference between the participant population of both groups exists. The results indicated that there are no differences in participants’ characteristics (i.e., age, gender, familiarity with the faculty building, highest education level, previous experience with VR, and familiarity with any computer gaming) between the two groups. Thus, participants’ characteristics do not impact the further comparison of pedestrian wayfinding behaviour and user experience between the two groups.

4. Results

This study examined the difference in participants’ wayfinding behaviour and user experience as a result of the adoption of HMD VR and Desktop VR. To this end, pedestrian wayfinding behaviour is first analysed and compared in Section 4.1. Secondly, the user experience of VR is analysed and compared in terms of realism, simulation sickness, feeling of presence, and system usability in Section 4.2.

4.1. Pedestrian wayfinding behaviour

As mentioned above, pedestrian wayfinding behaviour can be evaluated based on three levels of metrics including decision making, observation behaviour, and wayfinding task performance. Using these metrics, this section presents an analysis of pedestrian behavioural data collected during the VR experiment, namely (1) pedestrian route and evacuation exit choice, (2) observation behaviour, and (3) wayfinding task performance.

4.1.1. Route and evacuation exit choice behaviour

In order to better understand pedestrians’ route and exit choice during the wayfinding tasks, this section analyses pedestrian route and exit choice during each task, including (1) the wayfinding strategy, (2) the usage of paths, (3) the usage of decision points, and (4) the usage of staircases.

1. ***Task 1***

Fig. 8 shows the aggregated movement trajectories of participants during the first task (room 4.02 – room 4.99), including the usage of paths and decision points. The central point strategy was employed by 24 (66.67%) participants in the HMD group and 24 participants (70.59%) in the Desktop group. These participants first moved along the corridor where their start position was. In the HMD group,12 participants (33.33%) used the direction strategy while 10 participants (29.41%) in the Desktop group used the direction strategy. They first moved in the direction of the target room. There was no significant difference in wayfinding strategies according to the Chi-square test, $X^2(1, N = 70) = 0.125, p = 0.98, phi = 0.04$.

Regarding the usage of paths, the Chi-square test showed there was no significant difference in the usage of paths between the Desktop group and the HMD group during task 1, $X^2(7, N = 287) = 1.62, p = 0.978, v = 0.08$.

Fisher exact test showed there was no significant difference in the usage of decision points between the Desktop group and the HMD group during task 1 ($p = 0.626, v = 0.31$). In total, the number of used decision points was 38 in the HMD groups and 34 in the Desktop group.

2. ***Task 2***

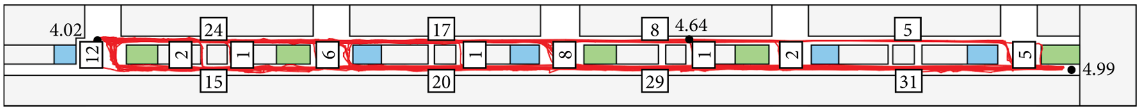
Fig. 9 shows the aggregated movement trajectories of participants during the second task (room 4.99 – room 2.01). In the HMD group and the Desktop group, 27 participants (75.00%) and 28 participants (82.35%) employed the floor strategy, respectively. The direction strategy was employed by 9 participants (25.00%) in the HMD group and 6 participants (17.65%) in the Desktop group. There was no significant difference in adopted wayfinding strategy according to the Chi-square test, $X^2(1, N = 70) = 0.561, p = 0.454, phi = 0.09$.

Fisher exact test revealed that there were no significant differences in the usage of paths ($p = 0.999, v = 0.16$), decision points ($p = 0.527, v = 0.52$), and staircases ($p = 0.999, v = 0.17$) between the Desktop group and the HMD group during task 2.

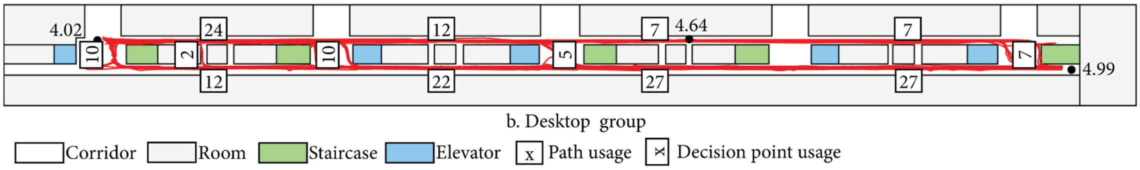
3. ***Task 3***

Fig. 10 shows the aggregated movement trajectories of participants during the third task (room 2.01 – room 4.64). In the HMD group, 26 participants (72.22%) used the floor strategy, and 10 participants (27.78%) employed the direction strategy. In the Desktop group, 33 participants (97.06%) employed the floor strategy and 1 participant (2.94%) employed the direction strategy. There was a significant difference in the wayfinding strategy between two groups according to the Chi-square test, $X^2(1, N = 70) = 8.144, p = 0.004, phi = 0.34$.

Fig. 10 illustrates the distribution of the usage of paths, decision points, and staircases in both groups. The Fisher exact test revealed that

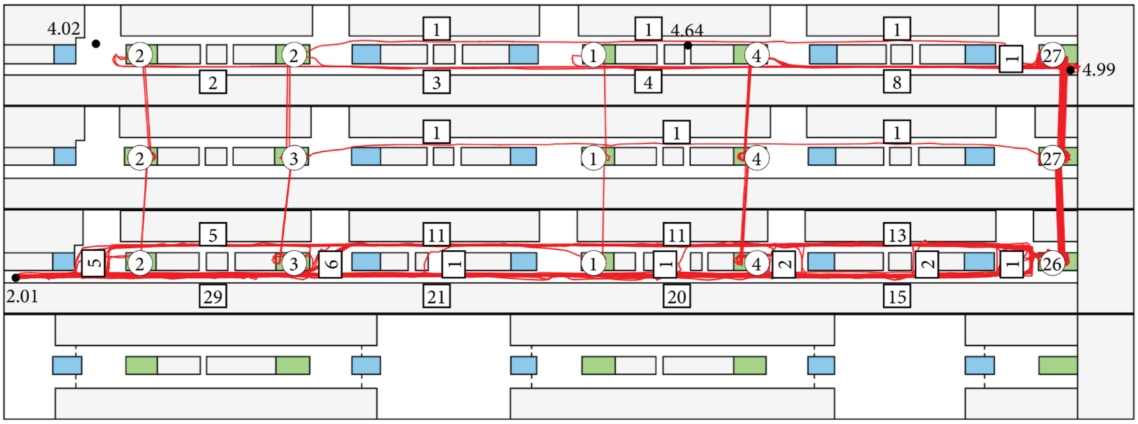


a. HMD group

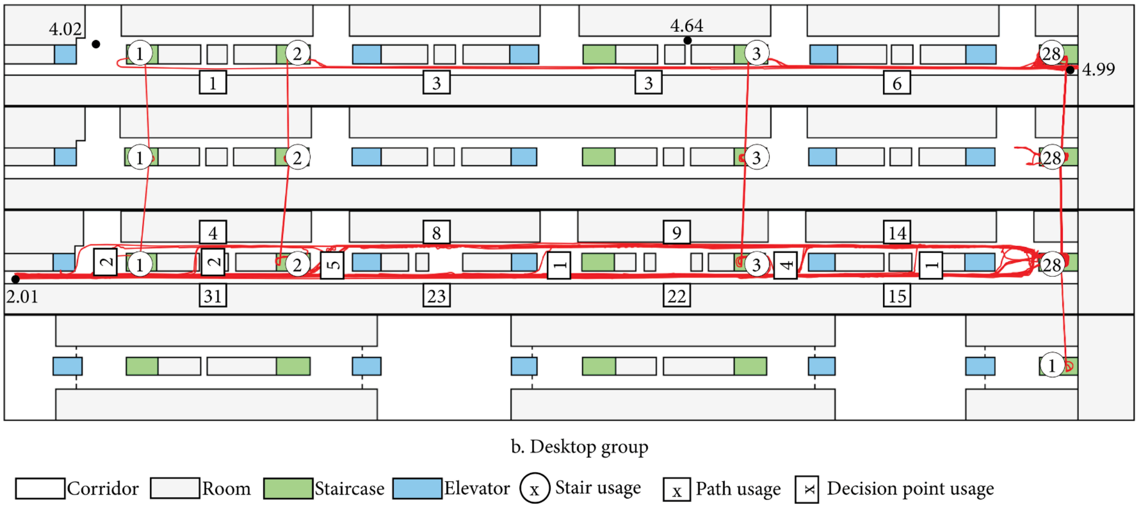


b. Desktop group

Fig. 8. Visualisation of the participants' movement trajectories and the frequency of path and decision point usage during task 1.



a. HMD group



b. Desktop group

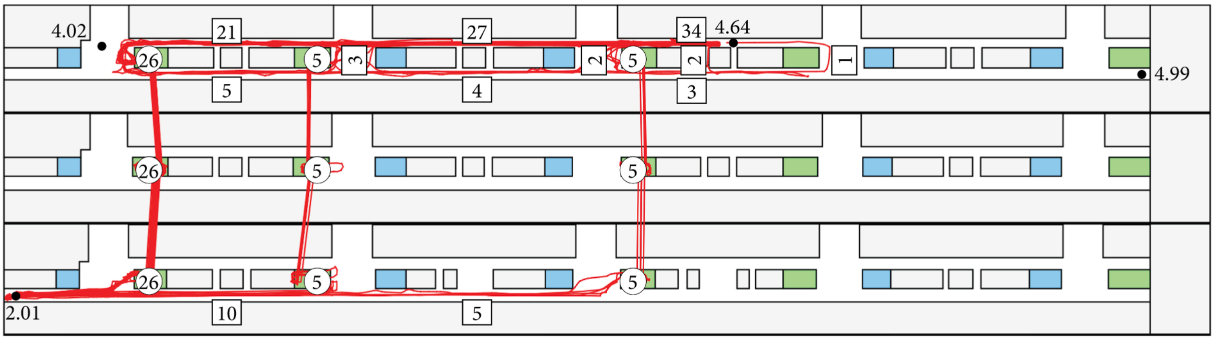
Fig. 9. Visualisation of the participants' movement trajectories and the frequency of staircase, path and decision point usage during task 2.

there was no significant difference in the usage of paths ($p = 0.119$, $v = 0.25$) between the Desktop group and the HMD group during task 3. However, there were significant differences in the usage of decision points ($p = 0.021$, $v = 0.92$) and staircases ($p = 0.002$, $v = 0.33$) between the two groups during task 3. These results indicated that although the usage of paths was similar, the usage of decision points and staircases were significantly different.

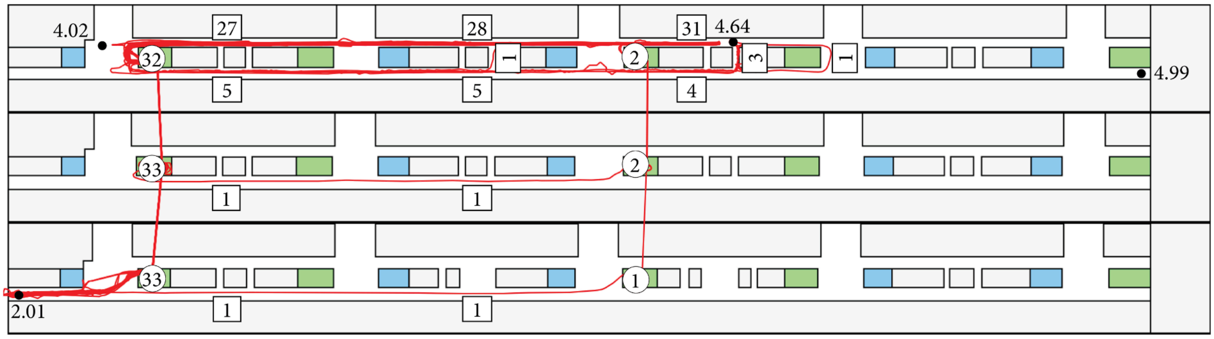
4. *Task 4*

Fig. 11 shows the aggregated movement trajectories of participants during the evacuation task (room 4.64 - an exit). Regarding the usage of the wayfinding strategy, all participants chose to go down first, thus the floor strategy was employed by both groups. The Chi-square test showed there were no significant differences in the usage of paths, $X^2(2, N = 72) = 0.230$, $p = 0.891$, $v = 0.06$, and the usage of staircases, $X^2(5, N = 210) = 0.686$, $p = 0.984$, $v = 0.06$.

Even though five main exits were available, only exits C (i.e., C1 and C2) and D (i.e., D1 and D2) were chosen, which are the nearest two exits for the participants. In the HMD group, 9 participants chose exit C1, 9 participants chose exit C2, 12 participants chose exit D1, and 6 participants chose exit D2. In the Desktop group, 8 participants chose exit C1, 11 participants chose exit C2, 8 participants chose exit D1, and 7 participants chose exit D2. There was no significant difference in the exit usage between the two groups using the Chi-square test, $X^2(3, N = 70) = 1.079$, $p = 0.782$, $v = 0.12$.



a. HMD group



b. Desktop group

Fig. 10. Visualisation of the participants' movement trajectories and the frequency of staircase, path and decision point usage during task 3.

4.1.2. *Observation behaviour*

For task 1, the distributions of the head rotation change $\overline{Y}$ of both groups were not normally distributed (Shapiro–Wilk test, $p < 0.001$). Thus, the non-nonparametric Mann-Whitney U test was performed, which showed that there was a significant difference in head rotation change between the two groups ($U = 372$, $p = 0.002$, $d = 0.44$). The average rotation change of HMD group ($M = 7.38°/s$, $SD = 4.00°/s$) was significantly higher than the Desktop group ($M = 5.55°/s$, $SD = 4.24°/s$). Fig. 12 shows the aggregated distributions of participants' gaze points during task 1. Here, room numbers (i.e., red dots along with the rooms), fire doors (i.e., red perpendicular in the corridors), and floor plans (i.e., red perpendicular near the floor plans) were the main attractions. Fig. 12, furthermore, illustrates that participants from the HMD group had denser gaze points near room numbers and fire doors, which indicated that participants had more 'looking around' behaviour and paid more attention to room numbers and fire doors in the HMD group than the Desktop group.

For task 2, the Shapiro–Wilk test rejected that the head rotation change of both groups followed a normal distribution ($p < 0.05$). The Mann-Whitney U test showed that there was a significant difference in the head rotation change between the two groups ($U = 461.5$, $p = 0.039$, $d = 0.17$). Participants had significantly higher head rotation change in the HMD group ($M = 10.71°/s$, $SD = 2.52°/s$) than the Desktop group ($M = 10.17°/s$, $SD = 3.73°/s$). Fig. 13 shows the aggregated gaze distributions of participants during task 2. The result of head rotation change is further supported by the gaze distributions, which illustrated that the AOI was smaller in the Desktop group than the HMD group. Moreover, the density of the resulting gaze points was higher in the HMD group. Thus, fewer room numbers and fire doors were scanned by the participants in the Desktop group.

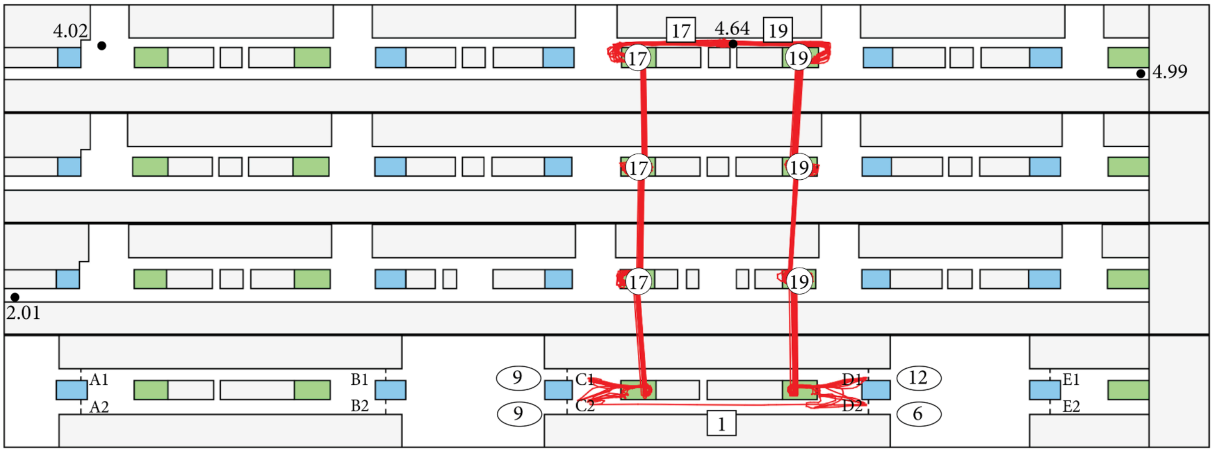
For task 3, the normal distribution of head rotation change was rejected for both groups (Shapiro–Wilk test, $p < 0.05$). The average head rotation change is $13.61°/s$ ($SD = 3.41°/s$) and $13.05°/s$ ($SD = 3.76°/s$) respectively in the HMD group and the Desktop group. The Mann-Whitney U test showed there was no significant difference in head rotation change between the two groups ($U = 538$, $p = 0.194$, $d = 0.16$). Fig. 14 shows the gaze distributions of participants during task 3. Also in this task, the gaze points of the room number, fire doors and floor plans were major attractions in the environment for both groups.

For the evacuation task (task 4), the normal distribution of head rotation change was rejected for the Desktop group (Shapiro–Wilk test, $p < 0.01$) but not for the HMD group (Shapiro–Wilk test, $p = 0.196$). The Mann-Whitney U test showed that there was a significant difference in rotation change between the two groups ($U = 304$, $p < 0.001$, $d = 0.91$). Participants had significantly higher head rotation change in the Desktop group ($M = 34.26°/s$, $SD = 7.87°/s$) than the HMD group ($M = 27.47°/s$, $SD = 7.06°/s$). Fig. 15 shows the gaze distributions of participants during task 4, which illustrates that exit signs were the major attractions during the wayfinding task (i.e., the red spheres in the corridor next to the staircases). In both groups, all participants chose to go down using the staircase at the right or left side of room 4.64 after the evacuation alarm was triggered. It also showed that participants made a quick decision to go down directly after seeing the exit signs.

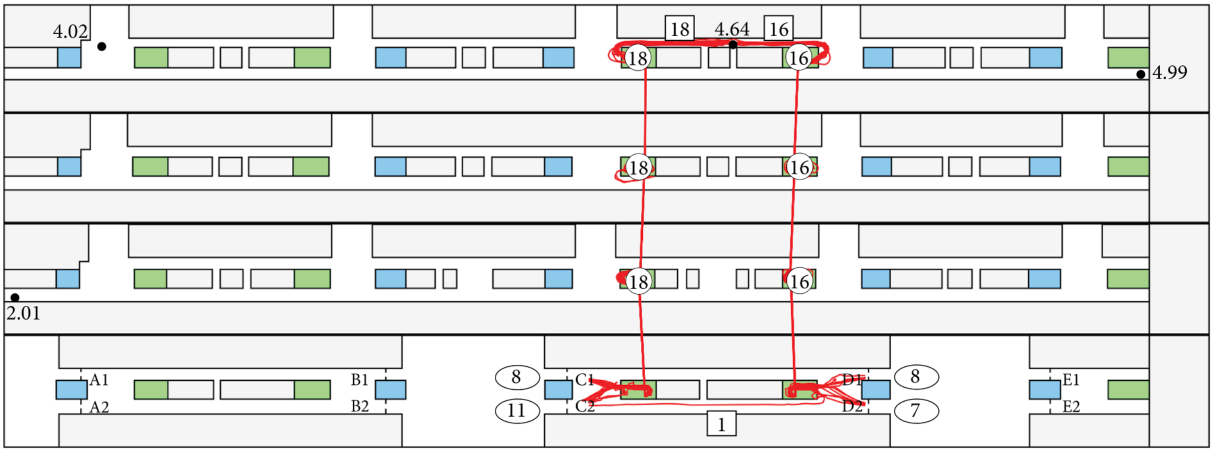
4.1.3. *Wayfinding task performance*

Participants' average travel time for each task are summarised in Table 2. For both groups, the distribution of travel time was not normally distributed (all $p < 0.05$). Consequently, the nonparametric Mann-Whitney U test was conducted, which showed significant differences in travel time during task 1 ($U = 215$, $p < 0.01$, $d = 0.97$), task 2 ($U = 203$, $p < 0.001$, $d = 1.23$), task 3 ($U = 164$, $p < 0.001$, $d = 1.11$), and evacuation task ($U = 316$, $p < 0.001$. $d = 0.62$). The tests indicated that participants from the HMD group spent significantly more time during each task than the Desktop group.

The average travel distance of participants during each task is displayed in Table 3. The travel distance for both groups was not normally distributed ($p < 0.05$). Thus, the Mann-Whitney U test was conducted which showed that there were significant differences in travel distance

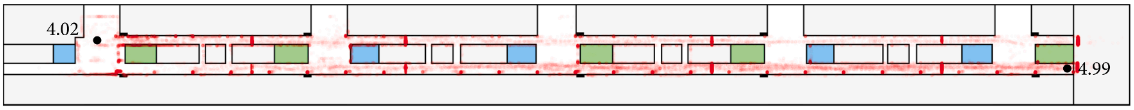


a. HMD group

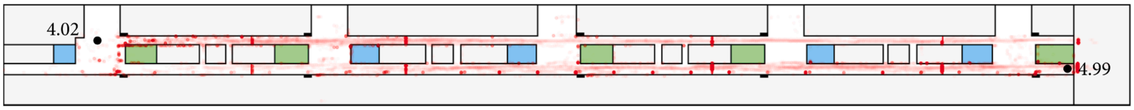


b. Desktop group

Fig. 11. Visualisation of the participants' movement trajectories and the frequency of staircase, path, decision point and evacuation exit usage during task 4.



a. HMD group



b. Desktop group

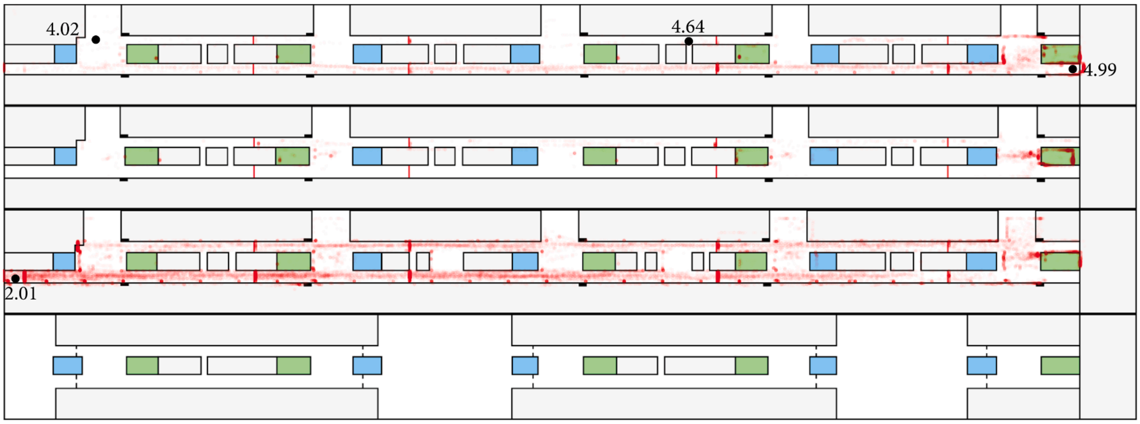
Fig. 12. Distribution of participants' gaze points during task 1.

between the HMD and the Desktop group during task 1 ($U = 286$, $p < 0.01$, $d = 0.69$), task 2 ($U = 248$, $p < 0.01$, $d = 0.85$), task 3 ($U = 209$, $p < 0.01$, $d = 0.76$), and evacuation task ($U = 428.5$, $p = 0.016$, $d = 0.34$). The results indicated that participants in the HMD group travelled significantly longer distances than the Desktop group during each task. Even though the difference in travel distance is 4.70 m on average, this corresponds to a difference in travel time of 16.95 s on average.

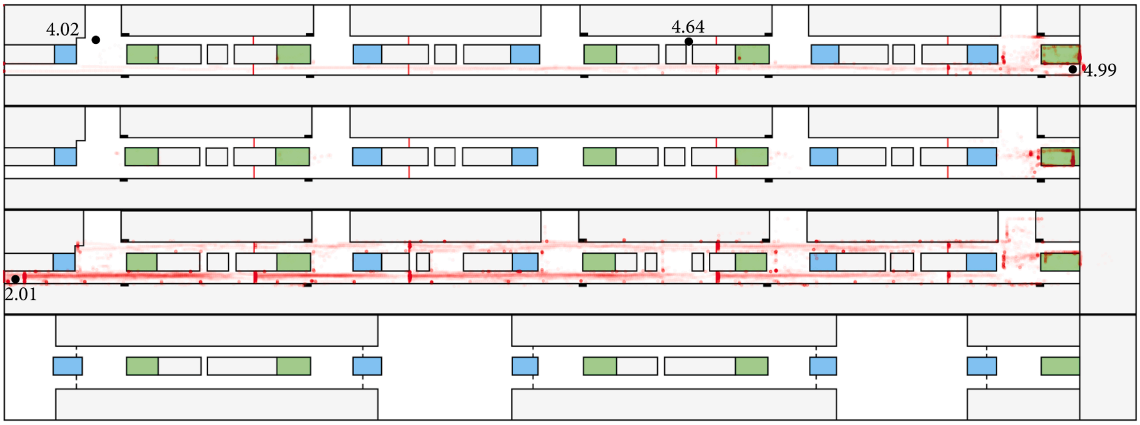
The average travel speed of participants during each task is displayed in Table 4. The normal distribution of travel speed was rejected for the Desktop group during all tasks and only rejected for the HMD group during task 1 and task 3 (Shapiro–Wilk test, $p < 0.05$). The result of Mann-Whitney U tests indicated that there were significant differences in average travel speed between two groups during task 1 ($U = 259.5$, $p < 0.01$, $d = 0.97$), task 2 ($U = 220$, $p < 0.01$, $d = 0.82$), task 3 ($U = 177$, $p < 0.01$, $d = 1.27$), and task 4 ($U = 304$, $p < 0.01$, $d = 0.80$). That is, the participants in the HMD group had significantly slower average speed during each task than the Desktop group.

4.2. *User experience*

In order to examine whether technological differences influence the user experience of VR, this section analyses the questionnaire data



a. HMD group



b. Desktop group

☐ Corridor ☐ Room 🟩 Staircase 🟦 Elevator ■ Floor plan | Fire door

Fig. 13. Distribution of participants' gaze points during task 2.

collected from the HMD group and the Desktop group, namely the face validity, the simulation sickness, the feeling of presence, and the system usability.

4.2.1. *Face validity*

The assessment of face validity included participants' reported answers of four items, namely the realism of the virtual building, the virtual furniture, the movement abilities, and the evacuation alarm sound (see Appendix B). A 5-point Likert scale ranging from 1 (not at all realistic) to 5 (completely realistic) was used by participants to rate the items, which is a typical scale for Likert response [116].

Table 5 shows the descriptive results of face validity for both groups. Overall, the average total score of the HMD group and the Desktop group was above 4 out of 5, which suggested the virtual environment had a high level of realism. Meanwhile, seventy-five percent of the participants graded the total score above 4 or higher, which strengthens the face validity results (see Fig. 16). The total score of the Desktop group was not normally distributed ($p = 0.043$), and the total score of the HMD group was normally distributed ($p = 0.088$). Thus, the non-nonparametric Mann-Whitney U test was performed, which showed that there was no significant difference in the average total score of face validity between the two groups ($U = 587.5$, $p = 0.387$, $d = 0.08$).

In addition, the score of all subscales was not normally distributed (all $p < 0.001$). The Mann-Whitney U test showed that the 'realism of the movement abilities' is significantly different between the two groups ($U = 458.5$, $p = 0.025$, $d = 0.46$). No significant differences existed related to the items 'realism of the evacuation alarm sound' ($U = 499.5$, $p = 0.054$, $d = 0.45$), 'realism of the virtual building' (U = 503.5, $p = 0.074$, $d = 0.34$), and 'realism of the virtual furniture' ($U = 525$, $p = 0.107$, $d = 0.30$).

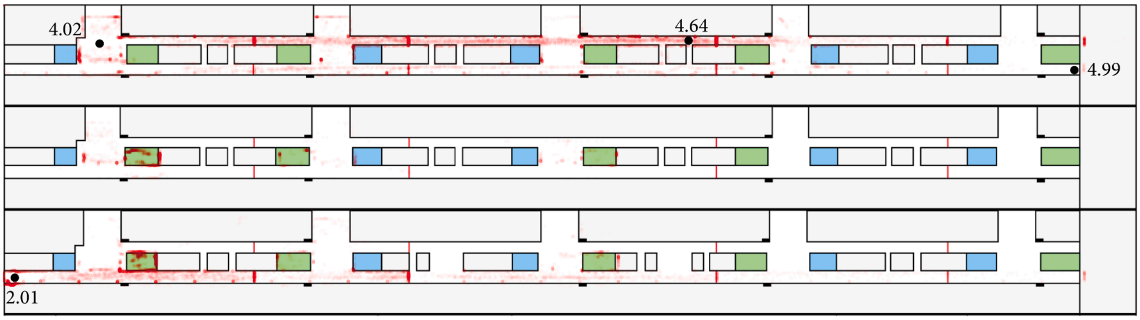
4.2.2. *Simulation sickness*

Simulation sickness is generally defined as the discomfort that arises from using simulated environments [117]. In order to investigate the potential for simulation sickness because of the usage of the VR, the Simulator Sickness Questionnaire [108] was used. Sixteen symptoms were rated respectively on a 4-point Likert scale from 0 (None) to 3 (Severe). Scores of these symptoms can be grouped into Nausea (N), Oculomotor (O) and Disorientation (D) subscales, as well as a total symptom score.

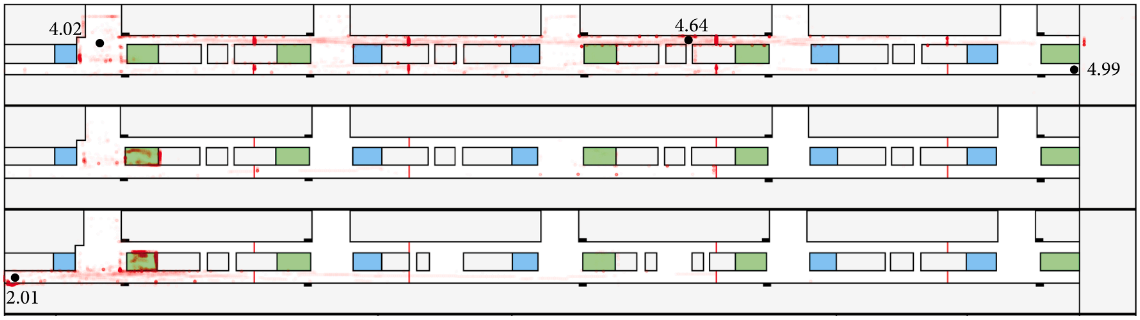
Table 6 shows the mean value and standard deviations of SSQ. For both groups, the distributions of the SSQ score were not normally distributed ($p < 0.001$). The Mann-Whitney U test showed that there was no significant difference in total SSQ score between the two groups ($U = 559.5$, $p = 0.269$, $d = 0.10$). Moreover, no significant differences in the subscales of Nausea ($U = 591$, $p = 0.397$, $d = 0.11$), Oculomotor ($U = 536.0$, $p = 0.181$, $d = 0.09$) and Disorientation ($U = 603.5$, $p = 0.460$, $d = 0.08$) were found between two groups. The boxplots in Fig. 17 showed that the Desktop group had more outliers on the higher score. We did not find a particular reason for the outliers (e.g., age, familiarity with VR or the building) and removing the outliers did not change the statistical results ($p > 0.05$).

4.2.3. *Sense of presence*

The Presence Questionnaire (PQ) [110] was used to assess participants' feeling of presence in the virtual environment. It includes four



a. HMD group



b. Desktop group

Fig. 14. Distribution of participants' gaze points during task 3.

subscales, namely involvement, sensory fidelity, immersion, and interface quality. The PQ consists of 29 questions and each question was reported from 1 to 7. The total score was counted by summing the reported scores of the 29 items.

Table 7 shows the statistical results of PQ for both groups. In the current study, the mean score of PQ was 146.00 ($SD = 13.63$) for the HMD group and 148.50 ($SD = 17.86$) for the Desktop group. The total score of PQ of the HMD group ($p = 0.44$) and the Desktop group ($p = 0.618$) was normally distributed. Therefore, the independent *t*-test was performed, which showed there was no significant difference in the total score of PQ between the HMD group and the Desktop group ($t = 0.661$, $p = 0.511$, $d = 0.16$).

All the sub-scale followed a normal distribution (all $p > 0.05$). Thus, the independent *t*-test was performed, which showed that there were no significant differences in the four subscales between the two groups. The statistics results of the *t*-test for both groups are shown in Table 7.

4.2.4. Usability

The System Usability Scale (SUS) questionnaire [109], which is commonly used as a usability questionnaire, was adopted in the current study to assess the usability of both VR technologies. The questionnaire consists of 10 items with responses on a 5-point Likert scale, from strongly disagree (1) to strongly agree (5). The total score of SUS ranges from 0 to 100.

The average total score of SUS was 83.75 ($SD = 11.92$) in the Desktop group and 82.01 ($SD = 11.10$) in the HMD group, which indicated the effective usability of both systems. The total scores of SUS in the HMD group ($p = 0.001$) and the Desktop group ($p < 0.001$) were not normally distributed. Accordingly, the Mann-Whitney U test was used to compare the average total score of SUS in both groups, which identified that there was no significant difference between the two groups ($U = 511.50$, $p = 0.119$, $d = 0.15$). Table 8 presents the mean scores and standard deviations of ratings for the ten items in the SUS. The first five items were worded positively, and the second five items were worded negatively. The item 'I thought the system was easy to use' received the highest average score in both groups; 'I found the system unnecessarily complex' and 'I needed to learn a lot of things before I could get going with this system' received the lowest score in, respectively the HMD group and the Desktop group. This indicated that both systems were easy and simple to use.

5. Discussion

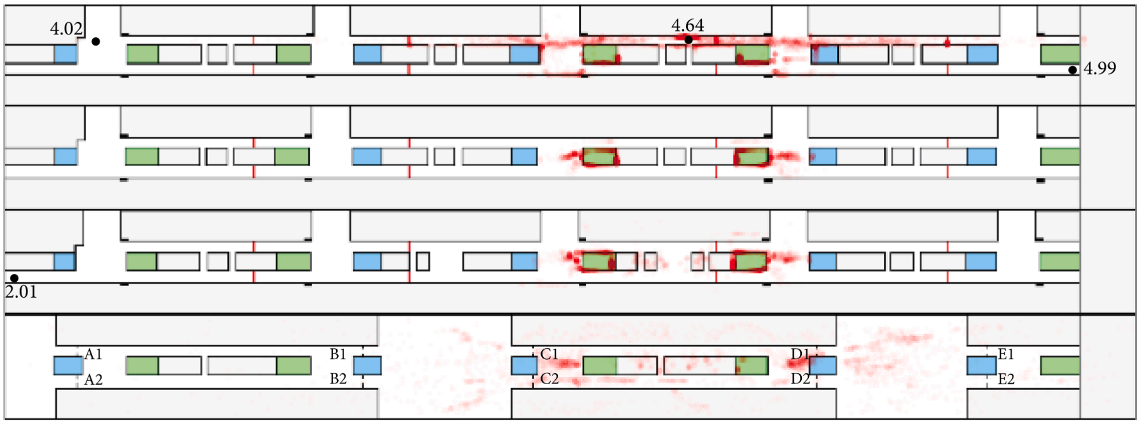
This paper aims to compare the adoption of different VR technologies for pedestrian wayfinding studies, via investigating the difference in pedestrian wayfinding behaviour and user experience. Wayfinding experiments with two groups of participants were conducted using either HMD VR or Desktop VR. Four hypotheses were formulated, namely there are significant differences in (H1) route and exit choice behaviour (i.e., wayfinding strategies, usage of paths, decision points, staircases, and exits), (H2) observation behaviour (i.e., head rotation and gaze point), (H3) wayfinding task performance (i.e., time, speed, and distance), and (H4) user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that used Desktop VR and the HMD VR. This section discusses the experimental results with respect to pedestrian behaviour and user experience to answer the above-mentioned hypotheses in Sections 5.1 and 5.2, respectively.

5.1. Differences in pedestrian wayfinding behaviour?

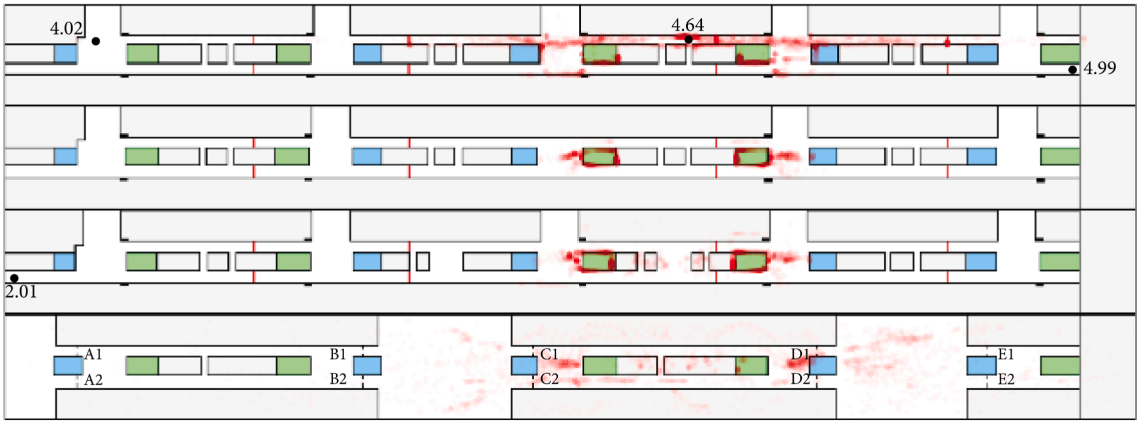
This study characterised the pedestrian wayfinding behaviour in the VR environment by means of a selection of metrics, namely route and exit choice behaviour (i.e., wayfinding strategies, usage of paths, decision points, staircases, and exits), observation behaviour (i.e., head rotation and gaze point) and wayfinding task performance (i.e., time, speed, and distance). Underneath, the findings pertaining to each metric are discussed and compared to the literature.

5.1.1. Difference in pedestrian route and exit choice behaviour

This study found a limited significant difference in terms of route and



a. HMD group



b. Desktop group

Fig. 15. Distribution of participants' gaze points during task 4.

Table 2
Means and standard deviations of travel time (s) in each task.

Task number	HMD group *Mean (SD)*	Desktop group *Mean (SD)*
Task 1	160.79 (20.19)	144.82 (11.12)
Task 2	201.30 (18.30)	179.09 (17.86)
Task 3	140.14 (24.02)	118.59 (12.59)
Task 4	66.67 (11.37)	58.59 (14.50)

Table 3
Means and standard deviations of travel distance (m) in each task.

Task number	HMD group *Mean (SD)*	Desktop group *Mean (SD)*
Task 1	188.68 (4.85)	185.27 (5.10)
Task 2	237.82 (5.52)	232.34 (7.28)
Task 3	163.13 (9.57)	156.05 (8.94)
Task 4	73.34 (8.77)	70.52 (7.80)

exit choice behaviour. Only significant differences pertaining to the detailed behaviour (i.e., wayfinding strategy, usage of staircase, and decisions points during task 3) were recorded. Therefore, hypothesis H1: there is a significant difference in route and exit choice behaviour (i.e., wayfinding strategy, paths, decision points, staircases, and evacuation exit choice) between the participants that adopted Desktop VR and HMD VR, was only partially confirmed. In particular, the usage of wayfinding strategies, decision points, and staircases were significantly different in

Table 4
Means and standard deviations of travel speed (m/s) in each task.

Task number	HMD group *Mean (SD)*	Desktop group *Mean (SD)*
Task 1	1.19 (0.11)	1.28 (0.07)
Task 2	1.19 (0.09)	1.32 (0.13)
Task 3	1.18 (0.13)	1.32 (0.08)
Task 4	1.12 (0.15)	1.24 (0.16)

Table 5
The mean value and standard deviations of the face validity questionnaire.

Item	HMD group *Mean (SD)*	Desktop group *Mean (SD)*
Total score of face validity	4.04 (0.36)	4.07 (0.42)
Realism of the movement abilities	3.17 (0.65)	3.50 (0.79)
Realism of the evacuation alarm sound	4.75 (0.44)	4.50 (0.66)
Realism of the virtual building	4.08 (0.60)	4.29 (0.63)
Realism of the virtual furniture	4.17 (0.56)	4.00 (0.55)

the case where the destination was not clear-cut.

Overall, the frequency of adopting a certain wayfinding strategy was found to be similar during task 1, task 2, and task 4. This study illustrates that floor strategy was employed most in wayfinding tasks involved floor changes. Moreover, the frequency of using the floor strategy increased with the task number. This finding can be explained by literature (e.g., [56,118]), which suggests that when a destination is unclear, the

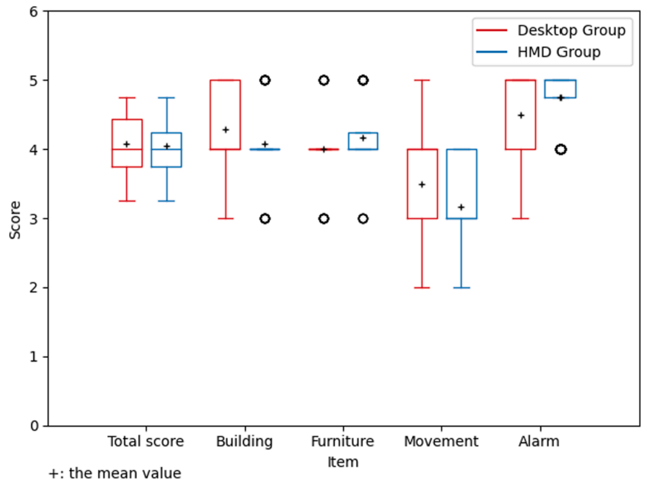


Fig. 16. Comparison of the boxplots of the face validity questionnaire for both groups.

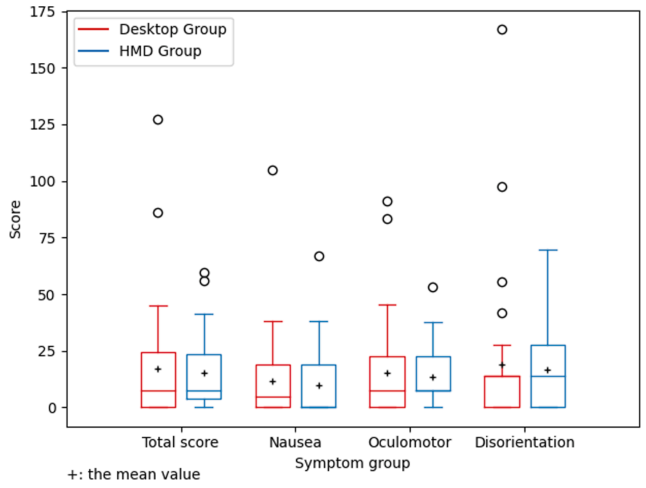


Fig. 17. Comparison of the boxplots of the SSQ questionnaire for both groups.

Table 6
The mean value and standard deviations of SSQ.

Item	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
Total score	15.06 (15.19)	17.27 (26.45)
Nausea	9.80 (14.69)	11.78 (20.07)
Oculomotor	13.69 (12.13)	15.38 (22.35)
Disorientation	16.63 (20.73)	18.83 (32.85)

Table 7
Subscales of PQ: Means and standard deviations (range from 1 to 7).

Item	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*	***t*-value, *p*-value, *d***
Involvement	4.81 (0.62)	5.08 (0.83)	1.531, 0.130, 0.37
Sensory fidelity	4.91 (0.87)	4.89 (0.82)	−0.123, 0.903, 0.02
Immersion	5.78 (0.50)	5.56 (0.68)	−1.625, 0.109, 0.37
Interface quality [a]	4.17 (0.97)	4.59 (1.04)	1.747, 0.085, 0.42

[a] Reversed items

proportion of participants who use the floor strategy increases. In this study, the destinations of task 1 and task 2 (i.e., the destinations were at the end of the corridor) were clearer, more regular and easier to understand than task 3 (room 4.64). Thus, the unclarity of task 3 might have resulted in a higher proportion of participants employing the floor strategy during task 3. Another explanation is that staircases were very visible and easily accessible in the current experimental environment, thus inviting participants to move to the destination floor at their earliest convenience. A significant difference was only found during task 3 regarding the wayfinding strategy. There are no published studies comparing pedestrian wayfinding strategies using different VR technologies. Some literature suggests that users in an immersive virtual environment were more likely to move directly between junctions [72], namely they like to use the 'straightest' route, which explained why participants from the HMD group were more likely to employ the direction strategy.

Considering the usage of paths, participant's behaviour was found to be overall similar between both groups. That is, both groups had a similar distribution of used paths during all tasks. Besides that, this study shows that participants preferred to use the wider and longer corridors for all tasks. In particular, the pedestrians refrained from using the smaller corridors that connected the two parallel main corridors and predominantly used the larger open areas to cross between the two main corridors. This is in accordance with studies of [64–67] that found participants preferred paths that are wider and with longer lines of sight.

The usage of decision points and staircase were overall similar for task 1, task 2, and task 4 between both groups. A significant difference was only found for task 3 regarding the usage of decision points and staircases. This is because more participants in the HMD group adopted the direction strategy than the Desktop group, which also leads to the different usage of decision points and staircases. Moreover, participants who used Desktop VR have a fixated view and a vantage point to observe the virtual building from the real-life environment, which means that they have a more accurate estimation of the movement direction [99].

Regarding the usage of exits during the evacuation, both groups showed similar choices. Meanwhile, the results show the usage of the exits was asymmetrical. That is, only the nearest four exits were used among ten available exits. This behaviour is in line with other studies that look at exit usage [21,119–121]. Meanwhile, in both groups, participants only chose the closet exits. This result is also consistent with recent findings that suggest pedestrians are overall more likely to choose the nearest exits and shortest routes [18,20,70,94,122–124].

5.1.2. Difference in observation behaviour

Regarding head rotation change, significant differences in tasks 1, 2, and 4 were found between two groups. Ultimately, hypothesis H2: there is a significant difference in observation behaviour (i.e., head rotation and gaze point) between the participants that adopted Desktop VR and HMD VR, was only partially confirmed.

Generally, room numbers, floor plans, fire doors, and evacuation exit signs were the major attractions for participants to find their way in the virtual environment. This finding is consistent with literature that suggests people pay more attention to salient landmarks and information that aids navigation [66,125]. More head rotation changes were identified in the HMD group than the Desktop group during tasks 1 and 2. This can be explained by literature, which suggests that viewers use a desktop have a higher degree of expectation regarding the direction in which they are likely to travel [99]. The result is consistent with navigation studies that suggest that participants feel the fully immersive VR setting is more natural and intuitive to look around [15,82,126]. Participants in the Desktop group needed to press the mouse to change their view to rotate and their physical view is still fixated on the computer screen in front of them [44], while participants in the HMD group required fewer efforts and felt more natural to rotate (i.e., simply move their head).

Yet, contrary to our expectation, during the evacuation task, participants from the Desktop group had significantly more head rotation changes than the HMD group. This can be explained by two reasons. Firstly, it might be that participants of the HMD group did already observe the environment more during previous tasks, thus less

Table 8
Mean scores and standard deviations of the SUS questionnaire.

Item	HMD group *Mean (SD)*	Desktop group *Mean (SD)*
I thought the system was easy to use	4.39 (0.80)	4.65 (0.65)
I felt very confident using the system	4.33 (0.83)	4.56 (0.75)
I would imagine that most people would learn to use this system very quickly	4.11 (0.92)	4.44 (0.99)
I found the various functions in this system were well integrated	3.92 (0.73)	4.15 (0.61)
I think that I would like to use this system frequently	3.39 (1.15)	3.13 (1.09)
I think that I would need the support of a technical person to be able to use this system	1.56 (0.81)	1.44 (0.99)
I thought there was too much inconsistency in this system	1.56 (0.77)	1.38 (0.60)
I found the system very cumbersome to use	1.53 (0.81)	1.76 (1.10)
I needed to learn a lot of things before I could get going with this system	1.36 (0.80)	1.26 (0.62)
I found the system unnecessarily complex	1.33 (0.53)	1.62 (1.10)

'observing' was required in the follow-up tasks due to the learning effect. Secondly, with increasing task complexity (i.e., find an exit during an emergency), the participants from the Desktop group increased their levels of head rotation to acquire the necessary information from the environment in order to evacuate and find the location of exits. Meanwhile, the results show that when tasks get more complex (i.e., tasks 3 and 4), it is generally more intuitive and natural for participants to look around.

5.1.3. *Difference in wayfinding task performance*

With respect to the task performance, the results revealed that significant differences existed in participants' travel time, travel distance, and average travel speed during all tasks. Ultimately, hypothesis H 3: there is a significant difference in wayfinding task performance (i.e., time, speed, and distance) between the participants that adopted Desktop VR and HMD VR, was confirmed.

The results indicate that participants had more efficient task performance in the Desktop group compared to the HMD group. This finding is consistent with studies that reported better navigation efficiency in a Desktop VR than an immersive VR [15,44,127]. It problematizes the simple assumption that more immersive VR leads to better performance. This might be explained by three reasons. First, participants in the HMD group used more decision points compared to the Desktop group. As Suzer et al. [29] stated, if a traveller chooses a longer route, the usage of decision points increases, which also leads to more difficulties in the wayfinding task. Therefore, the increase of decision points can cause an increase in the travel distance and travel time. Second, according to the result of head rotation change and gaze points, participants in the HMD group have more 'observing behaviour' (i.e., higher head rotation change, higher density of gaze points, and bigger AOI) than those in the Desktop group, which might cause longer travel time. Moreover, the significant difference in travel time is consistent with [14–15], which found participants spend longer time using HMD VR compared to using Desktop VR in wayfinding tasks. Third, the participants from the Desktop group used a standard computer and had more experience with computer gaming, while most of the participants from the HMD group had never or seldom used VR before. Therefore, participants from the Desktop group operated the system more easily, which might cause a shorter travel time.

5.2. *Differences in user experience?*

This study characterised the user experience of the participants by means of four assessments, namely the face validity, simulation sickness, sense of presence, and usability. Underneath, the results pertaining to each questionnaire are discussed and compared to the literature.

5.2.1. *Face validity*

Regarding the face validity questionnaire (see Appendix B), participants in both groups reported an average score above 4 (total score: 5), which confirmed the face validity of both VR setups. This was also confirmed by comments from participants, for instance, 'I feel like walking in the faculty'as well as 'I feel the urge to get out of this building' and 'I want to be out of this building as quick as possible' for the evacuation task. The realism of movement abilities from the Desktop group was significantly higher than the HMD group. This finding might be caused by the 'step-by-step' movements in the HMD VR, which cause participants to experience less continuous movements at low walking speeds compared to the smoother movements in the Desktop VR. The score of the face validity questionnaire of the current study is similar to other pedestrian-related studies that also used HMD VR (e.g., [117,128]). However, no comparative 'face validity' studies addressing different VR technologies for pedestrian studies have been found in the literature.

5.2.2. *Simulation sickness*

With respect to the simulation sickness, the average total score of SSQ in both groups was relatively low considering the maximum total score of the SSQ is 236 [129]. Compared to the study of [21,130], participants from the current study had lower SSQ scores although they had longer exposure time in the virtual environment.

Although it is generally assumed that motion sickness increase from Desktop VR to HMD VR [131], that is not the case in the current study. We found that there was no significant difference in SSQ between both groups, and participants reported a higher average score in the Desktop group than the HMD group. This surprising finding can be explained by three reasons from the literature. First, according to sensory conflict theory [132], simulation sickness is a result of conflicts between visual inputs and vestibular inputs. While participants in the Desktop group were moving in the virtual environment, their bodies remained sitting in the real world. Thus, participant's visual system indicated that they were moving, however, their vestibular system told the body it was stationary. In the HMD group, participants continuously rotated their heads in real life to change the direction of movement in the virtual environment, thus fewer sensory conflicts were expected. Second, participants in the HMD group had more active searching behaviour (indicated by the observation behaviour) than the Desktop group. Literature suggests that active participants may experience fewer symptoms [99]. Third, there were more outliers of the SSQ scores of the Desktop group which might cause a, on average, higher SSQ score.

Besides that, in both groups, Disorientation received the highest score, followed by Oculomotor and Nausea. Although the Disorientation subscale is related to vestibular disturbances, such as dizziness and vertigo, high disorientation may be an indicator that participants experienced higher levels of virtual presence [133]. The relatively high disorientation score might result from response lags. The current experiment tasks involved changing floors and some turning movements on the stairs in the virtual building, which are key sources of disorientation about one's heading and position in a building. The relation between disorientation and floor changes was also found in Hölscher et al. [58].

5.2.3. Sense of presence

In terms of the feeling of presence, the results revealed that participants in both groups experienced a similarly high level of presence. Moreover, the PQ scores in the current study are also slightly higher than the studies that also used VR technologies to study pedestrian behaviour (e.g., [71,79,117]). When studying the subscales of PQ, the subscale 'Immersion' received the highest scores in both groups, which identifies that participants felt enveloped by, included in and interacted realistically with the virtual environment. In literature, generally the Desktop VR is categorised as 'non-immersive' VR and the HMD VR is 'immersive VR'. Yet, although the average score of the sub-scale Immersion was slightly higher in the HMD group in the current study, we did not find significant differences between two groups. This finding indicates that both VR technologies provided a similar immersion effect to participants. Our finding is in agreement with the study of [43], which showed that Desktop VR can also provide a good sense of presence to users.

We think there are two potential reasons for the finding that participants from the Desktop group reported similar levels of presence as the HMD group. One explanation is provided by literature, which suggests that when users are more comfortable and less focused on the interaction with VR technology itself (and more with their task), the feeling of presence increases [42]. In our study, the wayfinding tasks force participants' attention away from the interaction with VR. However, in the HMD group, participants needed to wear a headset all the time and proactively rotate their heads to search for information, while participants in the Desktop group sat comfortably in front of a screen, and simply used a mouse and keyboard to move. It means that participants in the HMD group might be less focused on the wayfinding tasks because they were distracted by the headset. A recent discussion by [134] provides another potential explanation, namely presence is related to users' expectations. People normally have a lower expectation of fidelity and 'realism' of non-immersive VR systems than immersive VR systems. Thus, the lower expectations on Desktop VR limit the negative reports on the feeling of presence when using Desktop VR.

5.2.4. Usability

Participants confirmed the usability of the two systems were both at an 'excellent level', according to the interpretation of the SUS score made by Bangor et al. [135], which confirmed that both VR setups had good usability. Meanwhile, the SUS score of both groups is higher than the studies of [21,97,117,136], which are the only four studies that measured SUS regarding the usage of VR in pedestrian behaviour. In both groups, the item 'I thought the system was easy to use' received the highest score, which indicate that both VR setups were easy to use. The slightly higher average score of participants in the Desktop group might be due to their previous experience using a computer, as suggested by literature [97]. That is, participants were more familiar with the display, mouse, and keyboard interface.

To summarise, there were no significant differences in terms of realism, simulation sickness, the feeling of presence, and usability between the two groups. Thus, hypothesis H4: there is a significant difference in user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that adopted Desktop VR and HMD VR, was rejected in this study.

5.3. Implications

Based on the key findings of this study, we highlight several theoretical and practical implications that are both relevant for pedestrian wayfinding research and human–computer interaction research.

5.3.1. Implications for theory

This study provides several theoretical implications for pedestrian wayfinding behaviour study and human–computer interaction. Firstly, this study provides empirical evidence that VR can be used to collect pedestrian wayfinding data in complex and multi-level buildings. Compared to VR studies featured more simplified environments (e.g., [14–15,39]), the current study shows that it is possible to collect adequate behavioural data in complex environments with high experimental control and let participants experience the virtual world in an immersive and engaging way. Secondly, this study identifies that it is possible to collect detailed behavioural data (i.e., movement trajectory, head movement, and gaze points), personal characteristics (e.g., age, gender, and familiarity with VR), and user experience (i.e., realism, simulation sickness, feeling of presence, and usability) using a VR research tool in combination with questionnaires, which is difficult to achieve under real-world conditions. This provides proof that pedestrian researchers can collect comprehensive data sets featuring multi-dimensional behaviour data simultaneously and provide researchers with new perspectives to understand pedestrian wayfinding behaviour. Moreover, this study provides exemplars of designing VR experiments regarding the experimental set-up that combines the usage of VR technology and questionnaire to study pedestrian wayfinding behaviour and human–computer interaction. Thirdly, this study shows that when applying VR to study pedestrian behaviour, it is also worthy and important to quantitatively investigate the interaction between people and technologies. Human performance in the virtual environment is influenced by the interaction between the individual and the virtual environment (e.g., presence, usability, realism, and simulation sickens) [92–93]. For previous studies that investigated the interaction between people and VR technologies, some were qualitative or exploratory, or they only considered limited perspectives. The current study combines four different questionnaires and compares these perspectives quantitatively. In contrast to previous VR comparison studies (e.g., [99,131,137]), the realism, simulation sickness, presence, and usability in the current study was overall similar between the HMD and the Desktop group. When applying VR, researchers should take extra caution when making assumptions about the interaction between people and VR technologies in various contexts.

This study identifies significant differences in wayfinding task performance between the HMD and the Desktop group. Participants of the Desktop group navigated more quickly and efficiently during all wayfinding tasks. Meanwhile, pedestrian route and exit choice behaviour (i.e., usage of wayfinding strategy, path, decision points, staircase, and exit) were found to be overall similar during the first two and the evacuation tasks. Our study shows that for 'simpler' wayfinding tasks in multi-level buildings, pedestrian route and exit choice behaviour can be measured effectively using a more simple and less expensive Desktop VR. It indicates that for large-scale virtual environments, the benefits gained from increasing immersion may not be as prevalent as suggested in the literature (e.g., [15,137]). Furthermore, the user experience (i.e., realism, simulation sickness, presence, and usability) was overall similar between the two groups. These findings imply that studies that investigate pedestrian route and exit choice behaviour of 'simple' wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. Researchers can choose the best practice between HMD VR and Desktop VR base on their budget, existing equipment, and technical supports.

However, the findings regarding the comparison of the wayfinding strategy and observation behaviour imply that differences can appear, especially when (more complex) searching behaviour is triggered. In particular, there were differences in route choice (i.e., wayfinding strategy, decision point, and staircase) during the task where the location of the destination was not clear-cut. Meanwhile, participants who used HMD VR had more head rotation changes and observation behaviour during the first two tasks, while participants in the Desktop group had higher head rotation changes during the evacuation task. Thus, in cases where the wayfinding task become more complex and searching behaviour are important factors that aid wayfinding, there may still be advantages to use immersive VR. One is advised to carefully consider the differences in behavioural outcomes between both VR technologies when investigating wayfinding behaviour for more ‘complex’ wayfinding tasks (i.e., requires more spatial understanding). The findings highlight that if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting (HMD VR in our case) needs to be ensured in order to allow natural observation of the environment.

5.3.2. Implications for practice

This study provides insights for designing infrastructure and signage to facilitate wayfinding in complex buildings. This study found that room numbers, floor plans, and fire doors were the main attractions for participants to find their way in a multi-level building. This information helps to identify locations where pedestrians search for information and determine what environmental features they look at in order to inform their wayfinding process. These insights could be useful for practitioners who are involved in planning complex buildings to design effective signage in complex and large-scale buildings. Additionally, our study illustrates that floor strategy was employed dominantly in a multi-level building and pedestrians preferred to use the wider corridors over narrow ones. These findings regarding the usage of wayfinding strategies in a multi-level environment provide empirical evidence for professionals to predict and plan the main navigational flow evenly when a complex network of paths and decision points exist.

Moreover, this study provides proof that VR can be used to study pedestrian wayfinding behaviour and collect valid behavioural data in multi-level buildings. The combination of VR, BIM, and digital twin can be used for engineers through their design process to test the interaction between pedestrians and the built environment that is either too complex to test in real life (e.g., evacuation intervention) or hypothetical scenarios that do not exist today (e.g., new building designs) [12]. With the advantages provided by VR, such as the flexibility to simulate a variety of contexts and repeatability to conduct experiments with similar settings, it helps engineers deal with the increasing complexity of the modern engineering systems [138] and evaluate the design, which can be used to improve the design in an early stage of the design process before it is finally implemented. Therefore, provide engineers benefits of shortening development times, lowering construction costs, and construction risks.

6. Conclusion and future work

This study investigated differences in pedestrian wayfinding behaviour in a multi-level building and user experience of the VR technology in order to compare the adoption of HMD VR and Desktop VR for pedestrian wayfinding studies. In particular, pedestrian behavioural data (i.e., pedestrian route and exit choice behaviour, observation behaviour, and wayfinding task performance) and user experience data (i.e., realism, simulation sickness, presence, and usability) were compared between two groups of participants, where one group used the HMD VR and another group used the Desktop VR.

This study provides the first direct comparison between VR technologies regarding the differences in behavioural outcomes of pedestrians in a multi-level building and user experience between the adoption of different VR technologies. It provides the first solid empirical evidence of direct comparison between HMD VR and Desktop VR on the resulting wayfinding behaviour in a multi-level building, which can have an important implication for future investigation of pedestrian wayfinding and evacuation behaviour in complex buildings. The comparison between HMD VR and Desktop VR implies studies that investigate pedestrian route and exit choice behaviour of ‘simple’ wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. However, if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting (e.g., HMD VR) is recommended in order to allow natural observation of the environment.

Based on the key findings, we highlight several contributions of the current study. Firstly, this study applies emerging technologies to study pedestrian wayfinding behaviour. Our findings show that one can study pedestrian wayfinding behaviour in complex environments (even in emergency situations) using VR with high experimental control and still collect comprehensive data (i.e., movement trajectory, head rotation, gaze point, and user experience). This supports researchers and engineers to leverage their understanding of pedestrian behaviour in complex environments with new possibilities and perspectives. Secondly, the current study provides a quantitative and comprehensive comparison of pedestrian wayfinding behaviour and user experience as a result of the adoption of different VR technologies. It offers both theoretical underpinnings of the similarities and differences in pedestrian wayfinding behaviour using different VR technologies and practical suggestions for researchers who are interested in applying VR. Thirdly, this study provides clear Desktop VR and HMD VR use-cases of designing VR experiments regarding the experimental set-up, which combines the usage of VR technology and questionnaire to study pedestrian wayfinding behaviour and user experience. The combination may assist researchers in associating between pedestrian behaviour and human–computer interaction in order to better understand the usage of VR in the pedestrian field and formalize complex engineering knowledge.

Yet, there are several limitations of the current study. Firstly, in order to quantitatively measure the advantage of using HMD VR for complex wayfinding tasks, future studies should directly compare pedestrian behaviour in real and virtual environments. Due to COVID-19, it has until now been impossible to conduct the field experiment with an identical setting as the VR experiment in the faculty building. Secondly, comments made by the participants during the experiment reveal that additional elements can potentially make the current virtual experience more realistic, such as the presence of other pedestrians and the interaction with other people. In the present study, the virtual environment did not include other agents. Thus, it would be interesting to investigate the impact of VR technology on pedestrian wayfinding behaviour, while including the interaction with other pedestrians. Thirdly, the gazing behaviour of participants was only studied qualitatively in this study and was based on head rotations alone. In future studies, incorporation of precise eye-tracking technologies would allow for a more in-depth (quantitative) analysis of gazing behaviour, such as gaze time, gaze quantity, and gaze sequences. This would improve our understanding pertaining to pedestrians’ virtual attention in the environment and pedestrians’ decision-making process during wayfinding tasks. Moreover, the combination of behavioural data and physiological data may provide additional insights and new perspectives for wayfinding behaviour. For instance, integrating VR technologies with physiological sensing technologies (e.g., heart rate, electroencephalogram sensors, and biosensors) enables researchers to study participant’s wayfinding behaviour in combination with their mental and physical states in the virtual environments with stimuli (e.g., light, sound, signals, and text messages). Lastly, although no differences in personal characteristics were found between the two groups, literature does suggest personal characteristics could influence wayfinding behaviour (e.g., [78,79]). Therefore, future work should explore the impact of individual differences (e.g., familiarity with the environment, gender, and age) on pedestrian wayfinding behaviour in a complex multi-level building to gain a better understanding of individuals performing wayfinding tasks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. List of questions related to participant's characteristics

Are you familiar with the building of the Civil engineering and geosciences Faculty?

The highest education level you achieved.

Are you familiar with any computer gaming?

How often do you experience a virtual reality environment (e.g., gaming, training, entertainment)?

Appendix B. Face validity questionnaire

Instruction: Please characterize your experience in the virtual environment with a 5-point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply.

1. How realistic is the virtual building?

1 is Not at all realistic, and 5 is Completely realistic

2. How realistic is the virtual furniture (chairs, doors, etc.)?

1 is Not at all realistic, and 5 is Completely realistic

3. How realistic is the visual experience of the movement abilities?

1 is Not at all realistic, and 5 is Completely realistic

4. How realistic is the evacuation alarm sound?

1 is Not at all realistic, and 5 is Completely realistic

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